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Connecting Land-Based Networks to Ships

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THESIS

CONNECTING LAND-BASED NETWORKS TO SHIPS

by

Panagiotis Chatzigiannis

September 2012

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13. ABSTRACT (maximum 200 words)

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When a ship is near shore, it can use alternative methods of communicating with the shore network, which are typically faster and cost less. Examples of these methods are 802.16 WiMAX, 2G/3G cellular networks and Persistent Systems' Wave Relay. The purpose of this thesis is to evaluate all of the methods available, in terms of cost, range, bandwidth, quality of service (QoS) and reliability, by an experiment taking place in Monterey Bay. The experiment results are then used to determine which method would be best suited for various use cases.

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CONNECTING LAND-BASED NETWORKS TO SHIPS

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ABSTRACT

Today it's important for ships at sea to be able to communicate and exchange information with a shore network, like file transferring, database access, e-mail, web/intranet browsing or video conferencing. Navy ships might even want to send a live video feed from the field. To accomplish this, most ships use satellite communications, an expensive and slow method.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACK	Acknowledgement
ADNS	Automated Digital Network System
ARQ	Automatic Repeat request
ASN	Access Service Network
BE	Best Effort
BER	Bit Error Rate
BGAN	Broadband Global Area Network
CENTRIXS	Combined Enterprise Regional Information Exchange System
CID	Connection Identifier
CMAC	Cipher-based Message Authentication Code
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSN	Connectivity Service Network
DAMA	Demand Assignment Multiple Access
EAP	Extensible Authentication Protocol
EDGE	Enhanced Data rates for GSM Evolution
EGPRS	Enhanced GPRS
ertPS	Extended Real-time Packet Services
FAN	Floating Area Network
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GEO	Geostationary orbit
GGSN	Gateway GPRS Support Node

GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GUI	Graphical user interface
HARQ	Hybrid Automatic Repeat request
HF	High Frequency
HLR	Home Location Register
HMAC	Hash-based Message Authentication Code
HQ	Headquarters
HSCSD	High-Speed Circuit-Switched Data
HSPA	High Speed Packet Access
LAN	Local Area Network
LEO	Low Earth Orbit
LOS	Line Of Sight
MAC	Media Access Control
MANET	Mobile Ad Hoc Networking
ME	Mobile Equipment
MEO	Medium Earth Orbit
MS	Mobile Station
MSC	Mobile Switching Center
NPS	Naval Postgraduate School
OFDM	Orthogonal Frequency Division Multiplexing
PoE	Power over Ethernet
PSTN	Public Switched Telecommunications Network
QoS	Quality of Service
R/V	Research Vessel

RS	Reed Solomon
rtPS	Real-time Packet Services
RTT	Round-Trip Delay
SDU	Service Data Unit
SFID	Service Flow Identifier
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SNR	Signal to Noise Ratio
TA	Timing Advance
TDMA	Time Division Multiple Access
TO	Timeout
VoIP	Voice over IP
VRL	Visitor Location Register
VSAT	Very Small Aperture Terminal
WAN	Wide Area Network
W-CDMA	Wideband-CDMA
WiMAX	Worldwide Interoperability for Microwave Access

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I. INTRODUCTION

A. PROBLEM DESCRIPTION

Most ships today have built-in local-area networks (LANs) that support the ship's basic networking needs. Navy ships, for example, have a LAN that is used for combat systems integration or for message distribution. The usefulness and functionality of the ship's LAN can be extended significantly if that LAN could become a subnet of a wide-area land-based network.

Examples of ways to implement a network connection between a ship and a land-based network are satellite communications, WiMAX, commercial radio data networks, and cellular networks (either 3G or 4G). Each of these operates differently and has associated cost, range, access control, throughput, and reliability characteristics.

This thesis evaluates several such technologies to connect a shipboard LAN to a land-based network. The equipment/hardware needed for each is described, a thorough analysis of each proposed connection implementation is presented, and the various alternatives in terms of cost, range, bandwidth, quality of service (QoS) and reliability are compared. Furthermore, experiments are conducted using cellular networks, satellite communications, 802.16 WiMAX and Persistent System's proprietary Wave Relay. The results of the experiments are used to determine the method that would be best suited for various use cases.

B. THESIS OBJECTIVES

The main question that is addressed in this research is the following: "What is the best method of connecting a ship's LAN to a land-based network in terms of available bandwidth, reliability, operating range from shore, and QoS?"

Corollary questions to be answered in pursuit of this question are as follows:

- What equipment/hardware is required to connect a ship's network to a land-based network using satellite communications, WiMAX, 3G cellular networks, and Wave Relay radio routers?

- Can these connection methods be implemented so that it automatically chooses the best method according to some specifications set by the user?
- What are the benefits and drawbacks of each connection method? Which provides the best speed and the lowest latency? Which method is more cost-effective?
- What are the security issues that might be considered in the case of Navy ships?
- What are the network topologies and architecture that will be most suitable in the case of Navy ships?

This research helps military users who operate their ships near coastal waters and want to make their Navy's warships a part of the military network for participating in the construct and maintenance of a common situational awareness between the ashore elements and the afloat elements. A ship connected with the shore network enables the ship's personnel access to functionality that they would normally have only if the ship was docked. Commercial ships can also benefit from this study, since a ship will be able to connect with its corporation's network. Indeed, many companies and organizations pursue this, as is shown in Chapter II of this thesis.

C. SHORT BACKGROUND

Wireless networking technologies like cellular networks, WiMAX, and satellite communications can be used to implement an integrated network between land and ships.

Cellular networks, since they are widely deployed and used, are probably the cheapest way to implement such a network. The infrastructure is already in place and only limited hardware needs to be purchased and installed in order to build such an implementation. The range of a 3G network, however, is typically limited to coastal operating range; and 2G, which supports very limited data capability, extends the range to just over the horizon. As a result, such an implementation might only be useful if a ship is operating in coastal waters or in a geographical location that is always within at least the 2G range, like in the Aegean Sea where the many islands scattered around cover almost all areas. As commercial cellular networks may be vulnerable to eavesdropping, network security is another issue, particularly for Short Messaging Service text messages or signal jamming. This would be a concern for Navy ships.

WiMAX might offer a better range and throughput (theoretical range can be up to 30 miles), but a special infrastructure is needed. This translates to an increased overall cost. This 30-mile range, however, still necessitates operating the ship within a specified area. Wave Relay has similar characteristics in terms of range, bandwidth and cost.

Satellite communications, however, significantly mitigate limitations to the area within which the ship can operate. Latency and reliability issues, however, do arise, especially in the case of geostationary satellites, which introduce a propagation delay of nearly 500ms. This delay causes problems in TCP/IP connectivity. Congestion may be perceived high due to this delay resulting in unnecessary packet retransmissions. In addition, satellite communications are generally more expensive. As a general rule, they would be preferred only if the other methods are not available, serving as a fallback capability.

The initial results suggest that Wave Relay's ad hoc networking capability worked well out to about 15 Km, given the limitations placed on its range by the use of the omni-directional antenna for the mobile station. WiMAX was sufficient for close-in communications, again limited by the use of the omni-directional antenna for the mobile node. Both, however, were impacted by line-of-sight constraints, such as tree lines. Finally, 3G-based cellular mobile hotspots provided significant capability out to almost 20 Km.

D. THESIS OUTLINE

The thesis is organized as follows: Chapter II provides the necessary theoretical background for the technologies proposed to connect a ship with a shore network, providing the concept and terminology description that will be used throughout this thesis. It also gives examples of related projects, either military or commercial, that are related to the ship-to-shore connectivity problem.

Chapter III explains the experiment described above, explaining its geographical locations, its architecture, the hardware specifications and the experiment procedures that were followed.

Chapter IV describes the results of the experimentation conducted and data gathered from the experiment, as well as the problems encountered during its execution.

Chapter V provides conclusions of this research, summarizing its results, as well as making recommendations for future work.

II. BACKGROUND AND CURRENT CAPABILITIES

In Chapter 1, some ways to connect a ship with a shore-based network were briefly described. In this chapter, these ways and their architecture will be thoroughly analyzed. Some examples of recent or current projects related to the ship-to-shore connectivity problem will also be described.

A. OVERVIEW OF RELEVANT WIRELESS NETWORKING TECHNOLOGIES

1. IEEE 802.16 (WiMAX)

a. Architecture

Worldwide Interoperability for Microwave Access (IEEE 802.16 WiMAX) is an IP-based, wireless broadband access technology providing performance equivalent to 802.11 (WiFi) with the additional advantage of having coverage and quality of service (QoS) similar to that of the wide-area cellular networks. It has a range for broadband access of up to 30 miles (50 km) for fixed stations and up to 10 miles (15 km) for mobile stations.

The architecture of a WiMAX network, depicted in Figure 1, consists of the following three parts:

a. Mobile Stations (MS): Used by the end user to access the network.

b. Access Service Network (ASN): Comprises one or more base stations (BS), which are responsible for providing the air interface to the MS; and one or more ASN gateways acting as layer 2 traffic aggregation points within an ASN and forming the radio access network at the edge.

c. Connectivity Service Network (CSN): Provides IP connectivity to the Internet or to other public/corporate networks, as well as the entire IP core network functions. The CSN also provides the policy management for QoS and security functionalities.

QoS classes used by the 802.16 protocol include Best Effort (BE), used for data transfer and web browsing; Real-time Packet Services (rtPS), used for Streaming Audio/Video; and Extended Real-time Packet Services (ertPS), used for VoIP.

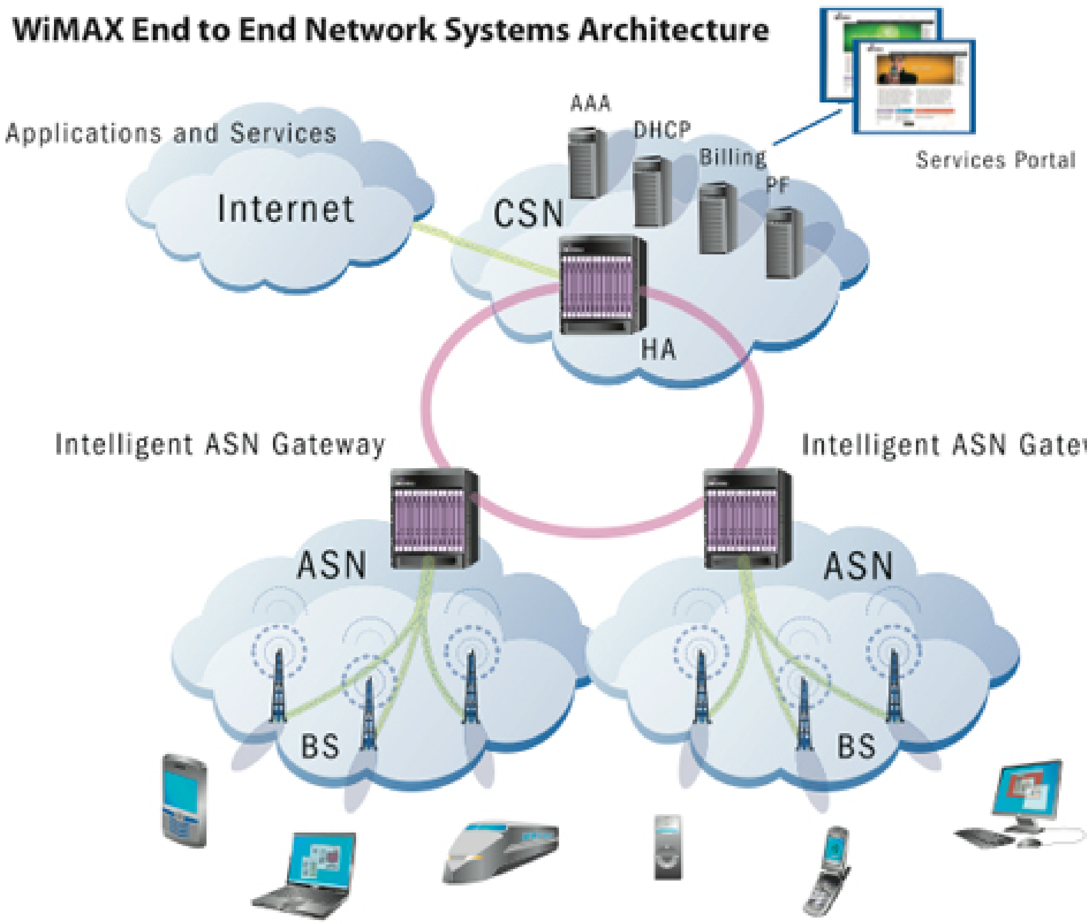

Figure 1. WiMAX architecture [From 2]

b. *Physical layer*

WiMAX physical layer is based on orthogonal frequency division multiplexing (OFDM), a special case of frequency division multiplexing (FDM) where the carrier signals are orthogonal to each other ($f_n = n \times f_1$, where f_1 is the lowest frequency). Among the advantages by using OFDM is reduced computational complexity, robust against narrowband interference and graceful degradation of performance under excess delay. OFDM, however, because it has high peak-to-average ratio, can result in nonlinearities and power inefficiencies. Also, it is susceptible to phase noise and frequency dispersion, so it is critical to have accurate frequency synchronization. Modulation schemes used include BPSK, QPSK, 16 QAM (Quadrature Amplitude Modulation) and 64 QAM. The spectrum used for WiMAX includes 2Ghz to 66Ghz. The stations can be either half-duplex or full-duplex, and the use of directional antennas can enhance range.

c. Error detection and correction

The error detection and correction is based on Reed Solomon (RS) Forward Error Correction, which is also used in consumer electronics, such as CDs, DVDs, Blu-ray Discs, in data transmission technologies, such as DSL, and in broadcast systems, such as DVB and ATSC. It's particularly useful for burst error correction at relatively high SNR. Its principle is described as follows: Assume a maximum detectable burst error of length L. Instead of computing parity checks over the bit positions, compute parity word checks over the corresponding word positions, effectively working in words instead of bits and having L independent codes. For example, if there is the following message,

10101010

01100110

00011110

11000110

+11110101

add the checksum 11100001 in order to get an error vector consisting of only 0's (00000000). This would detect an error up to 8 bits (1 byte). Reed-Solomon codes are classified as (n, k, t), where $n = 2^m - 1$ coded symbols (1 symbol = m bits), k < n the number of uncoded symbols, and $t = \left\lfloor \frac{2^m - k}{2} \right\rfloor$ the maximum number of errors that can be corrected.

Another technique used in conjunction with RS is Convolutional coding, which is achieved with k memory registers, each holding 1 input bit, and n modulo-2 adders, shown in Figure 2 as an example.

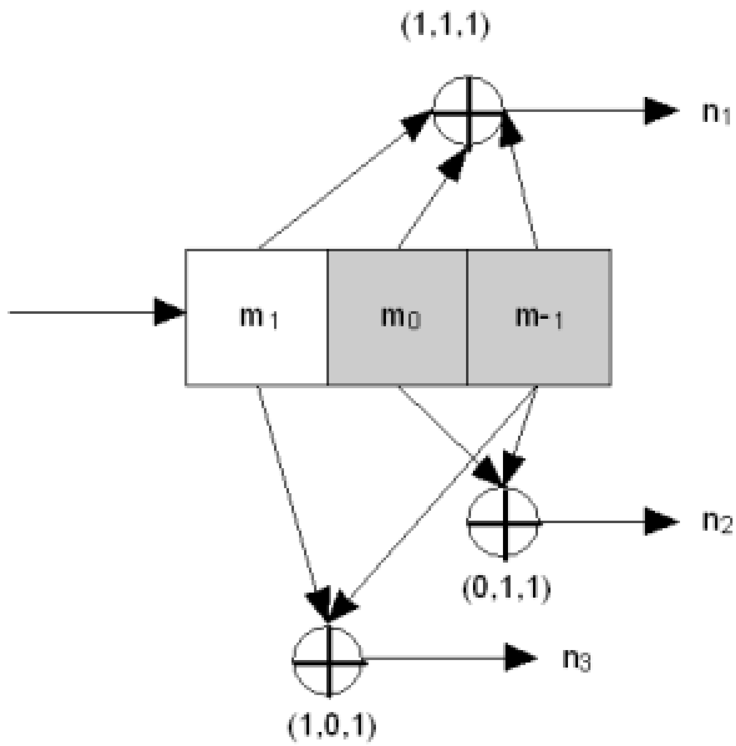

Figure 2. Convolutional coding example [From 2]

So in this example, $n_1 = m_1 + m_0 + m_{-1}$, $n_2 = m_0 + m_{-1,}$ $n_3 = m_1 + m_{-1,}$ the decoding process is done in the reverse way.

The error control method used in 802.16 is Automatic Repeat reQuest (ARQ). It uses acknowledgements (ACKs) and timeouts (TOs). If the sender doesn't receive an ACK before the TO, he re-transmits the frame (or packet) until the sender receives an ACK or exceeds a predefined number of re-transmissions. The types of ARQ protocols include Stop-and-Wait, Go-Back-N, Selective Repeat and Sliding Window. An example of the Selective Repeat protocol is shown in Figure 3.

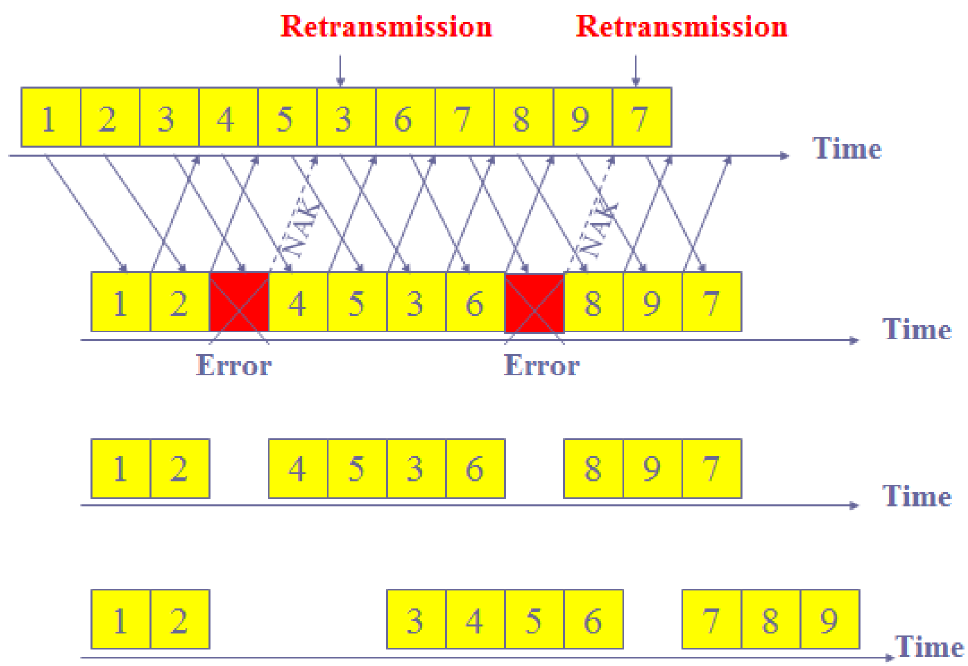

Figure 3. Selective Repeat Protocol [From 2]

WiMAX uses Hybrid Automatic Repeat reQuest (HARQ). In this scheme, forward error-correcting coding (RS and Convolutional coding) is used to correct a subset of all errors, and ARQ is used for detectable-but-uncorrectable errors. Hybrid ARQ has better performance when the signal is poor, but has lower throughput than ARQ when the signal is good.

d. Media Access Control (MAC) layer

The Media Access Control layer (MAC layer) in IEEE 802.16 is divided into 3 sublayers: the Service Specific Convergence Sublayer, the Common Part Sublayer, and the Privacy Sub-layer. The Service Specific Convergence Sublayer is the top sublayer, and classifies external network service data units (SDUs) and maps them to MAC SDUs. A service flow identifier (SFID) and connection identifier (CID) is used to provide QoS. The Common Part Sublayer assembles or fragments the SDUs (depending on transmitting or receiving) to MAC PDUs, which consists of a header, payload (optional) and CRC (optional). Each station has a 48-bit universal MAC address. The Privacy Sub-layer secures over-the-air transmissions to provide some protection against theft of service. It supports 3DES and AES schemes to encrypt user data. Device/user authentication is based on EAP (Extensible Authentication Protocol); RSA is used as the public-key encryption algorithm to perform the key exchanges, and the integrity of over-the-air control messages is protected by the use of cipher-based message authentication code (CMAC) or hash-based message authentication code (HMAC).

e. WiMAX mobility

IEEE 802.16 wasn't designed with mobility in mind; it was initially developed for LOS-based point-to-multipoint wireless broadband systems, and WiMAX networks were initially deployed for fixed and nomadic (portable) applications. These networks, however, were evolving to support mobility over time. The IEEE 802.16e-2005 standard defined a framework for supporting mobility management, and supported subscribers moving at vehicular speeds. The latest IEEE 802.16m (WiMAX Release 2), approved by IEEE on March 2011, supports peak data rates over 1Gbps (fixed) and over 100Mbps (mobile), up to 500km/h mobility, and, as of the writing of this report, it is being finalized.

Figure 4 shows where WiMAX stands in terms of mobility and speed related to WiFi 802.11 networks and the cellular networks. IEEE 802.11 networks offer a very high network throughput but are limited in terms of mobility, while cellular networks offer, by definition, the best mobility possible but at a usually lower speed. 802.16 WiMAX networks are effectively a solution combining these characteristics, offering a good throughput with good mobility. For the application of ship-to-shore communications, the amount of mobility offered should be sufficient, since a ship is moving at relatively slow speeds; commercial ships are usually traveling at speeds of 20–25 knots, a typical frigate or destroyer has a top speed of 30 knots, and even a fast missile-boat has a top speed of about 40 knots (about 46 miles/h or 74km/h). So all ships are well within the vehicular speed profile, and the IEEE 802.16e standard shouldn't have any problems for serving their mobility patterns.

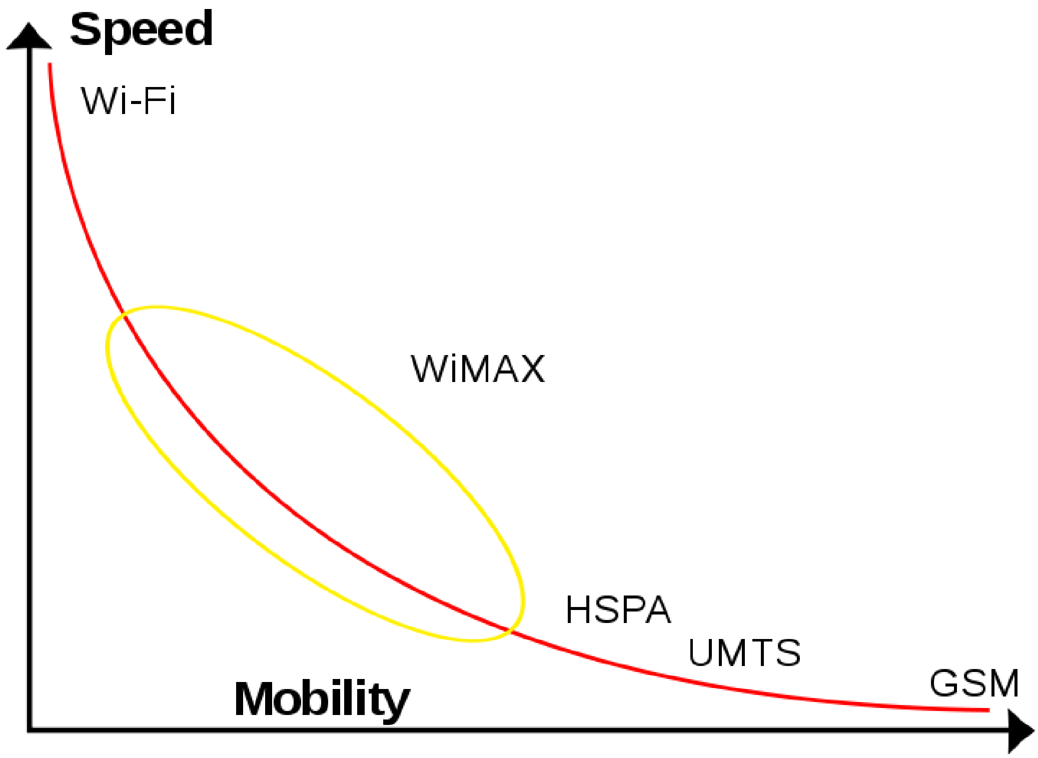

Figure 4. Mobility vs. Speed

2. 2G/3G Cellular Networks

a. GSM Architecture

The overall architecture for a GSM (Global System for Mobile Communications) cellular network, the most popular 2G technology worldwide, is shown in Figure 5. Its key functional elements are:

a. Mobile station, consisting of the mobile equipment (ME), such as a mobile device, and the subscriber identity module (SIM), which stores the subscriber's identification number.

b. Base station subsystem, consisting of a base transceiver station, which includes a radio antenna and a radio transceiver, and a base station controller, which handles the handoff process and reserves the radio frequencies. The base transceiver station defines a single cell, which can have a range between 100m in a city and 35km in rural environments. This difference is because the cells in densely populated are smaller, and the buildings affect the propagation conditions.

c. Core or Network subsystem, which connects the cellular network with the public switched telecommunications networks (PSTN). It is responsible for controlling the handoffs between cells in different Base Station Subsystems, authenticates the users, and manages worldwide roaming. The Mobile Switching Center (MSC) is the central element of the NS, and it is supported by the four databases it controls: i) Home location register (HLR) database, which stores the subscriber's information that belong to it, ii) Visitor location register (VLR) database, which stores the temporary location of the subscriber, iii) Authentication center database, which stores the authentication and encryption keys for all the subscribers in the VLR and HLR, and iv) Equipment identity register database (EIR), which keeps track of the type of equipment that exists at the mobile station, and helps disable stolen equipment.

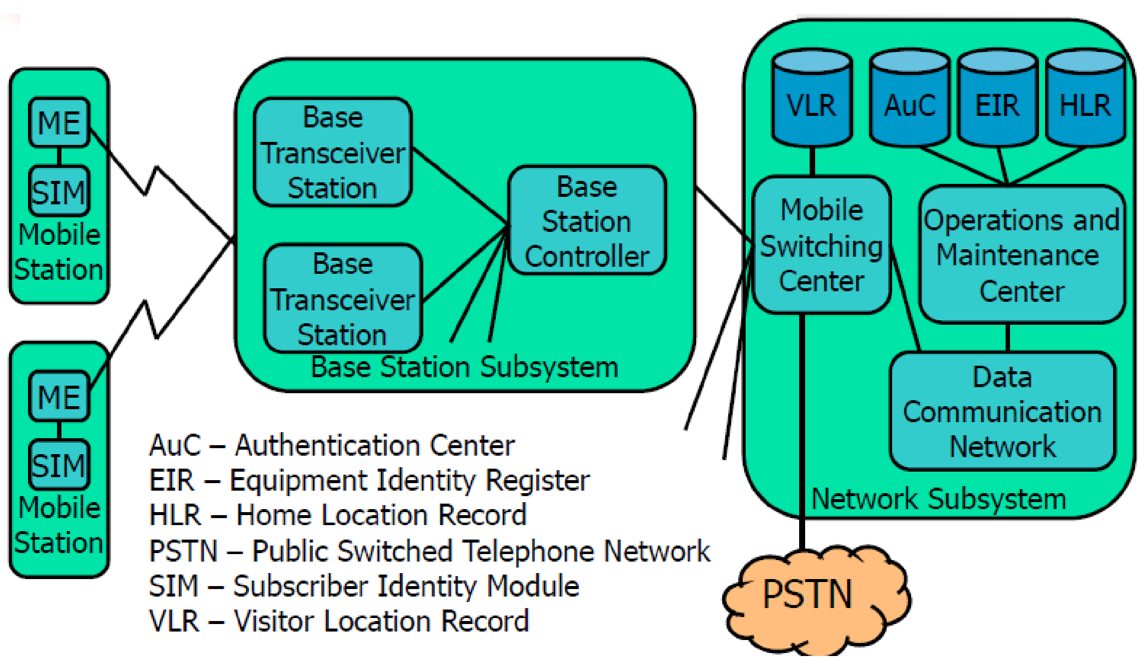

Figure 5. GSM architecture [From 10]

b. GSM Radio Link Aspects

GSM initially had been allocated a 25Mhz band for base transmission (935–960 MHz) and a 25Mhz band for mobile transmission (890–915Mhz), defined in 3GPP as GSM-900. Three more different bands, GSM-850, GSM-1800 and GSM-1900, named after the respective bandwidth, are each used in different parts in the world. Discontinuous transmission is used to save power consumption of the MS. Each channel has a bandwidth of 200kHz, which provides for 125 full-duplex channels, with 8 users per channel. The users access the network using a combination of frequency division multiple access (FDMA) and time division multiple access (TDMA). The GSM burst structure is illustrated in Figure 6, containing 148 bits in total, followed by 8.25 bits as guard time. Also, to prevent the MS from transmitting and receiving at the same time, the timeslots in the uplink are separated from the downlink by a three time-slot delay. In addition, a timing advance (TA) value is computed by the BSS to accurately determine the three time-slot delay, when the MS is far away from the BTS. This imposes a theoretical maximum range for GSM of 35km (22 miles) in order to avoid interference between time slots. This is particularly important for the ship-to-shore communication applications, as a ship operating outside the 22 mile radius from shore will not be able to communicate with the shore using GSM. Lastly, the carrier bit rate is 207.8kbps, the mobile unit's maximum power is 20 Watts and a convolutional error control coding method is used.

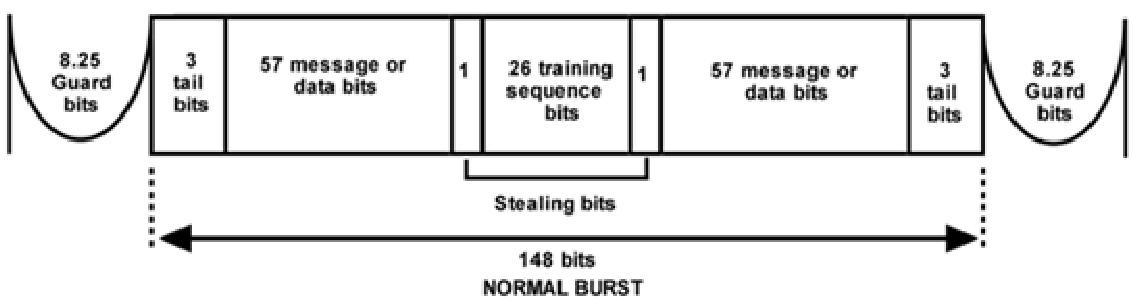

Figure 6. GSM burst structure [From 9]

c. GSM Data Services

The GSM standard supports 2 data service groups: short message services and bearer services. The bearer services have a limited data rate to 9.6Kbps, using a circuit-switched connection. These are insufficient to support Internet applications, like FTP file transfer or World Wide Web, so new GSM data protocols have been developed to provide efficient data capabilities over GSM. These protocols are the High-Speed Circuit-Switched Data (HSCSD) and the General Packet Radio Service (GPRS). HSCSD is a circuit-based protocol and it requires a software upgrade to the network. It increases the data rate to 28.8Kbps by allocating 3 TDMA time slots for each HSCSD connection.

GPRS, however, is packet-switched, and requires hardware upgrades to the existing GSM network. GPRS offers speeds up to 171.2Kbps, depending on the network availability, the terminal's capabilities and the channel coding scheme used. It's an important step in the evolution from GSM to 3G cellular networks, and there are already several GPRS implementations worldwide. The elements added to the existing GSM architecture are the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN). The SGSN is the MSC's packet-switched equivalent, and it's transmitting or receiving packets from the BSS to the MS. The GGSN provides the interfaces to external IP networks, such as the Internet, and has the routing information to tunnel the PDUs to the SGSN.

Another extension of GSM is Enhanced Data rates for GSM Evolution (EDGE), also known as Enhanced GPRS (EGPRS). It was first deployed on GSM networks in 2003, and it offers data rates two to three times higher than GPRS (up to 470Kbps for indoor and 144Kbps for outdoor operation, as most outdoor applications would involve mobility and greater free space loss). In EDGE, the BTS in the GSM architecture should be enhanced with a new power amplifier in the transmitter and a new equalizer in the receiver. EDGE adjusts to the connection quality to transmit the data as fast as possible, that is, it is "adaptive," but the high data rate it offers is only appropriate for indoor environments with pico- and micro-cell architecture extensions that offer good propagation conditions, as it has a smaller overhead devoted to error correction.

Together, these extensions to 2G GSM networks are often referred to as 2.5 or 2.75G. Third generation systems integrated both the data and the voice into a packet-switched network, moving away from the circuit-switch roots of the service.

d. Third-Generation (3G) Mobile Services

Third-Generation (3G) systems are designed to offer higher data rates that can support Internet access and wireless multimedia services, including audio, video and imaging. These rates offer 2Mbps for a fixed station, 384Kbps to a station moving at slow speeds and 144Kbps for vehicular speeds. For the application of ship-to-shore communications, the 384Kbps bandwidth should be considered.

Wideband CDMA (W-CDMA) is the 3G standard using the same core network as GSM and EDGE, although working at a different spectrum. This standard has the same principles as CDMA, but it’s more bandwidth-efficient. It was developed by NTT DoCoMo and launched in October 2001. The W-CDMA standard is further improved by High Speed Packet Access (HSPA), which supports peak downlink data rates up to 14 Mbps (HSDPA) using a 5Mhz channel, and peak uplink data rates up to 5.76 Mbps (HSUPA). HSPA typical average rates, however, are between 250Kbps and 750Kbps. Coverage range of HSPA is up to 5km (3 miles), which doesn’t make it very useful for ship-to-shore communication applications.

3. Satellite Communications

a. Overall Architecture – System Parameters and Configurations

A satellite communications system consists of at least two earth stations and at least one satellite that serve as relay stations. Satellites can be categorized according to their coverage area, or footprint (global or regional), service type (Fixed Service, Broadcast Service and Mobile service) and their usage (commercial, military, and experimental). Although a satellite system’s cost is relatively high, the transmission cost is independent of distance. The system offers a very high bandwidth and a very high quality of transmission, even after any short term signal outages or degradations due to the earth’s atmospheric conditions.

Satellite can also be classified according to their orbit shape (circular or elliptical), plane around the earth (equatorial, polar or inclined) and altitude (geostationary orbit – GEO, medium earth orbit – MEO and low earth orbit – LEO). Iridium satellite communication system is an example of LEO, while Inmarsat uses MEO and GEO. GEO satellites are the most common type. They are in a circular, equatorial orbit at a height of 35,786km above the surface, rotating at the same angular speed as the earth, resulting at an orbital period of 24 hours. This results in the satellite being stationary relative to the earth. While GEO have several advantages, like no Doppler effect resulting in frequency changes, simplified tracking and large coverage area (nearly ¼ of the earth's surface), they also have significant disadvantages, like signal attenuation due to the long communication distance, poor coverage of the earth's poles, and more importantly, a 0.5 sec round-trip delay (RTT), imposed by the signal's propagation delay as described in part C of this chapter [5], [11].

b. Satellite Frequency Bands and Transmission Impairments

Satellite communications systems use the frequency bands in Table 1.

Band	Frequency Range	Bandwidth
L	1 – 2Ghz	1Ghz
S	2 – 4Ghz	2Ghz
C	4 – 8Ghz	4Ghz
X	8 – 12.5Ghz	4.5Ghz
Ku	12.5 – 18Ghz	5.5Ghz
K	18 – 26.5Ghz	8.5Ghz
Ka	26.5 – 40Ghz	13.5Ghz

Table 1. Satellite communications frequency bands

Although higher frequency bands have increased bandwidth available, they generally suffer more from transmission impairments, as shown later. In addition, lower frequency bands, like L and S bands, have special characteristics useful for mobile service, such as refraction and greater penetration of physical objects. This results in greater demand for these frequency bands. Another fact is that uplink bands have higher frequency than downlink bands, since the higher frequency has greater free space loss, and the earth station, capable of transmitting at higher power, compensates for this loss.

In a satellite system's link analysis, the transmission impairments taken into account are:

a. Atmospheric attenuation. Rain and fog do not cause any problems in the lower frequency bands, but is a major concern in the upper frequency bands. There are several models that help predict attenuation caused by rain, which is necessary for the satellite communication system designer to determine the link availability and the link margin.

b. Free space loss, given by the equation

$$L = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi f d}{c}\right)^2$$

where λ: carrier wavelength, f: carrier frequency, d: propagation distance, c: speed of light. This equation shows that the free space loss increases as the distance between the satellite and the earth station increases (a disadvantage for GEOs, described above), and as the frequency increases.

c. Antenna tracking/pointing loss. In satellite communications, highly directional antennas are used, which define the satellite's footprint. If the antenna beam is not pointed accurately to the satellite or to the earth station, the antenna gain is lower.

d. Interference from other signals (e.g., adjacent satellite systems) [5], [11].

c. Satellite Network Configurations

There are 2 common satellite network configurations, depicted in Figures 7 and 8. In the first one, the satellite provides a point-to-point link between the 2 earth stations; while in the second, it provides communications between a single transmitter and many receivers. The second configuration can be modified to support 2-way communications between many earth stations, one of them having a central hub, also known as the very small aperture terminal (VSAT) system. The stations, equipped with VSAT antennas, share the satellite's transmission capacity to transmit to the station having the central hub. That hub station can then act as a relay between the other stations [5].

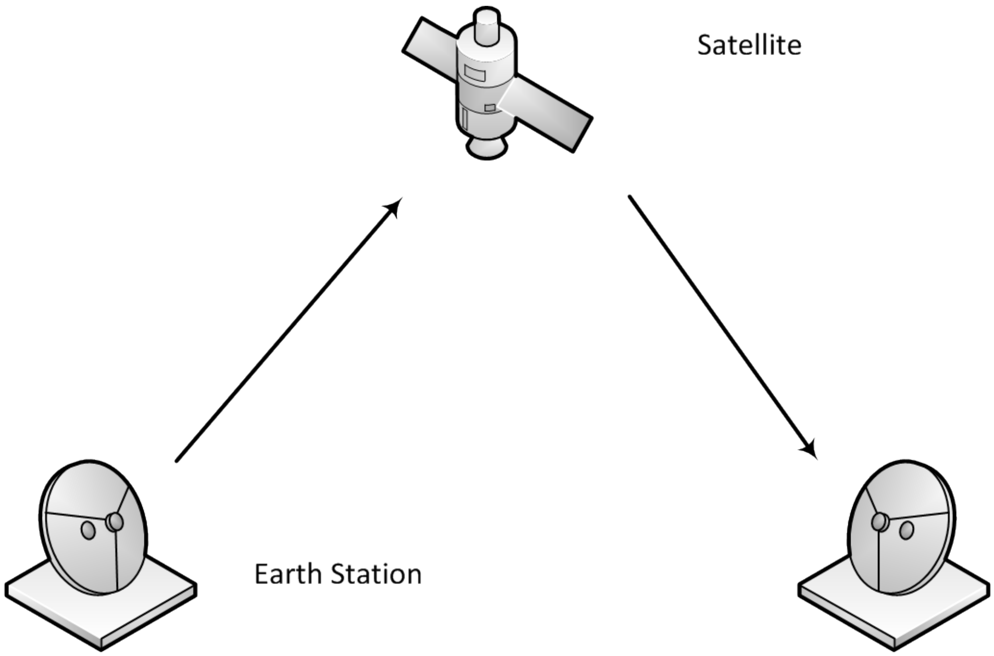

Figure 7. Satellite point-to-point link

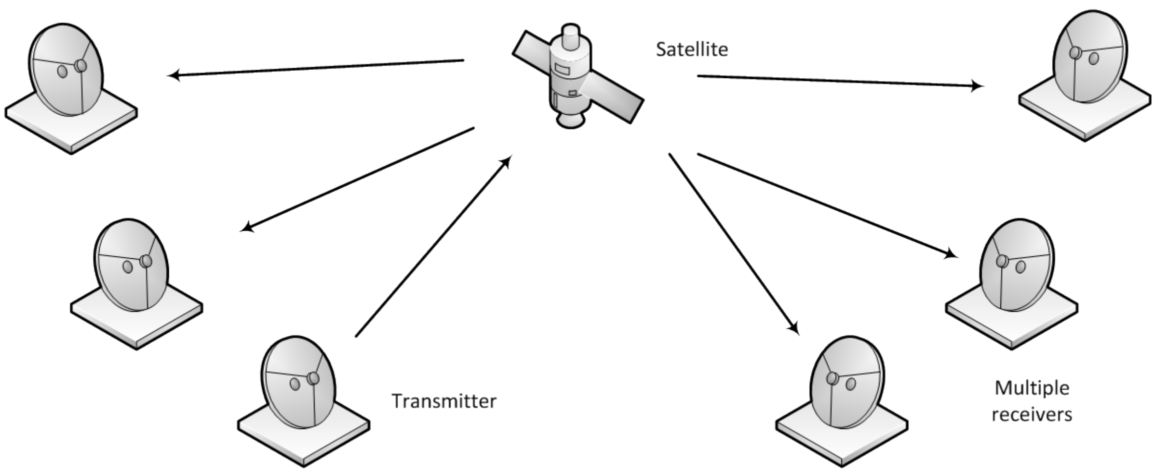

Figure 8. Satellite broadcast link

d. Capacity Allocation – Multiple Access Techniques

A satellite, typically having a large bandwidth, would divide it into channels of smaller bandwidth, each for a capacity allocation task. Each channel is going to be shared by many users, so there’s a need for multiplexing.

Frequency Division Multiple Access (FDMA) is the multiplexing scheme where each earth station transmits at different frequencies to the satellite (a guard band is used to prevent overlapping frequencies). As the satellite receives all the carriers making up its overall bandwidth, it amplifies them and retransmits them back. Each receiving earth station then selects their appropriate downlink carrier frequencies [11]. The number of available channels can be doubled employing frequency reuse, where each frequency assignment is used by 2 carriers with orthogonal polarization [5].

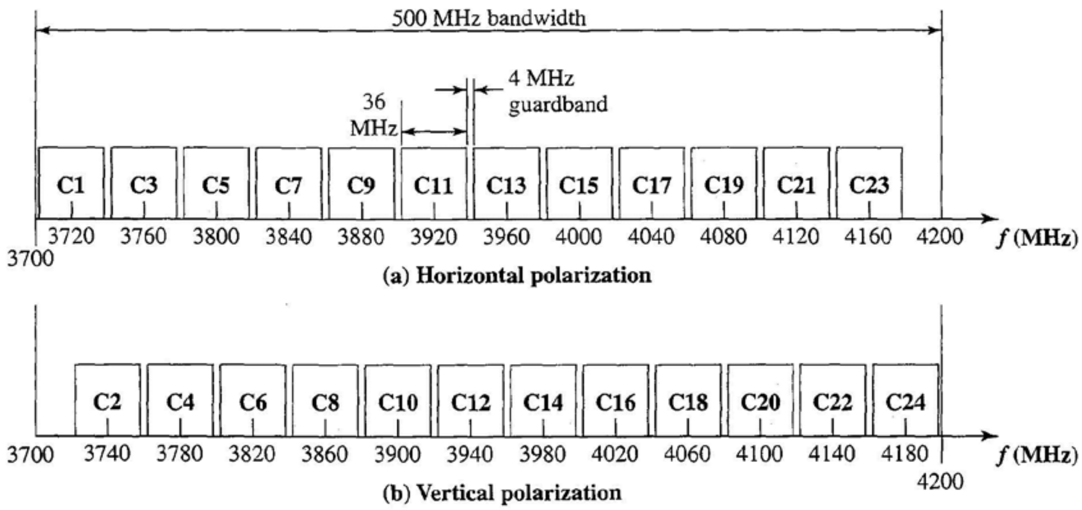

Figure 9. A satellite FDMA example with frequency reuse [From 5]

In Time Division Multiple Access (TDMA), the earth stations are assigned a periodic time frame for them to transmit. During that frame, they have the entire satellite bandwidth available to them. The timing has to be carefully synchronized, or there will be overlapping between the earth stations, so similar to FDMA, a guard time is assigned in the TDMA frame, as shown in the following figure. There are two reference bursts RB1 and RB2 to improve the reliability [11]. The advantages of the TDMA over FDMA multiplexing scheme include increased efficiency, as the guard time and control bits in TDMA take up less capacity than the guard bands in FDMA, less intermodulation noise, and cheaper equipment and hardware.

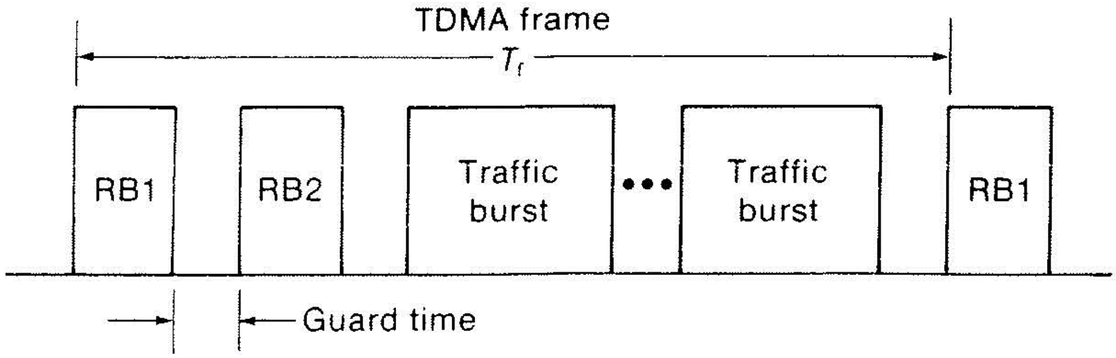

Figure 10. TDMA Frame Structure [From 11]

In some cases, the traffic burst preassignment might prevent reallocation of any unoccupied channels. This will have a negative impact on the satellite's utilization. To improve it, Demand Assignment Multiple Access (DAMA) might be used. In this scheme, each earth station is assigned its capacity on demand, which is released after it has finished transmitting or receiving. In addition, the capacity the station is assigned can be proportional to its traffic intensity, to further improve the system's overall efficiency [11]. A central control station might be used in the satellite communications system to control the assignment of the capacity, given by the burst length or the number of bursts per frame [12].

4. Persistent System's Wave Relay

Wave Relay is a "Mobile Ad Hoc Networking system (MANET) designed to maintain connectivity among devices that are on the move" [14]. It is a peer-to-peer mesh networking solution, using a proprietary algorithm. According to its manufacturer, it is designed to adapt in difficult environmental conditions to maximize connectivity and performance. It uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access algorithm, which avoids collisions by only transmitting after the channel is sensed to be "idle." Its physical layer is based on orthogonal frequency division multiplexing (OFDM), similar to WiMAX described earlier in this chapter.

The Quad Radio Router, which may be used to implement a large geographic coverage network suitable for maritime deployment, has up to 37Mbps throughput on a

20 MHz channel [15]. Its security algorithm is CTR-AES-256 HMAC-SHA-512 (Counter Mode AES encryption with a SHA-2 512bit hash-based message authentication code), and is validated by the governments of the United States and Canada.

B. TECHNOLOGIES ALREADY IN USE

1. U.S. Navy

a. Automated Digital Network System (ADNS)

The U.S. Navy's Automated Digital Network System (ADNS), serves as the interface for managing the Navy's tactical wide area network (WAN). It was introduced in 1997 when it made the connection between a ship and a shore network possible. It has been deployed on surface ships, submarines, aircraft and at Navy shore installations [17]. On the ship itself, the ADNS interfaces connect the ship's local area network (LAN) and the radio equipment. Similarly, on the shore it connects the radio equipment with the land-based switching networks. When it was initially developed, it used satellite communications as ship-to-shore link [16].

Figure 11. ADNS Overview [From 21]

The ADNS has been developed in three stages, or increments. The initial Increment I supported baseline routing and encryption, e-mail, web browsing and file transfer, all up to a 2Mbps bandwidth, and combined IP traffic from different enclaves to a Time Division Multiplexed (TDM) network across a single radio frequency path [16], [17]. Between 2004 and 2008, Increment II was developed (including sub-stages Increment IIa and Increment IIb) added load balancing capabilities, compression, application prioritization (Quality of Service – QoS), increased the maximum supported bandwidth to 8Mbps, transitioned from Proteon to Cisco routers and enabled a traffic flow over multiple satellite communication paths [16], [18], [19]. While all these Increments were developed and installed by the Navy itself, for Increment III, the Navy turned to a private sector contractor, the General Dynamics Company, hoping to improve the system even further. Its capabilities are to be enhanced even further by implementing "dual stack" IPv4/IPv6 architecture, a bandwidth up to 50Mbps, provide additional compression, but more importantly, expand the ability of the ADNS to use alternative, non-satellite paths. These paths can be high frequency (HF) radio, line of sight (LoS) data relay and even 802.11 network functionalities. A Navy ship, which has a limited bandwidth and its only option was satellite communications, now has the ability to manage its bandwidth, and utilize radio channels for ship-to-shore communications, a much cheaper and efficient solution.

b. Floating Area Network

Mobilisa, Inc. has developed for the U.S. Navy a way to enable ships at sea to communicate with each other, called Floating Area Network (FAN). Their technology is based on long-distance 802.11 antennas, having a line of sight range. Ships within range of each other create a mesh Ad-Hoc network that lets them communicate and exchange information directly without having to rely on slower and expensive satellite communications. Their technology was tested by the U.S. Navy during the exercise Trident Warrior in June 2008. Although this is not an example of direct ship-to-shore communication, this technology can be used in case a ship is out of range of shore cellular or WiMAX antennas, but another ship in the fleet is closer to the shore. This way, instead of using satellite communications, the FAN would be used to effectively extend the shore antennas' range, using ships as a relay [22], [23].

c. Combined Enterprise Regional Information Exchange System (CENTRIXS)

Combined Enterprise Regional Information Exchange System (CENTRIXS) was developed in 1998 as the first maritime Coalition Wide Area Network (CWAN). It was designed to provide secure and robust connectivity between U.S. and coalition forces, initially providing secure e-mail service over an INMARSAT satellite link for Navy ships and over dedicated circuits for allied shore commands. Later it was expanded to support data sharing through web browsing, e-mail with attachments, secure VoIP, collaboration and near-real-time situational data display and imaging. It has been the primary coalition network which was supporting Operation Enduring Freedom in 2002, a standard for information sharing between some 68 nations. CENTRIXS's architecture is illustrated in Figure 12.

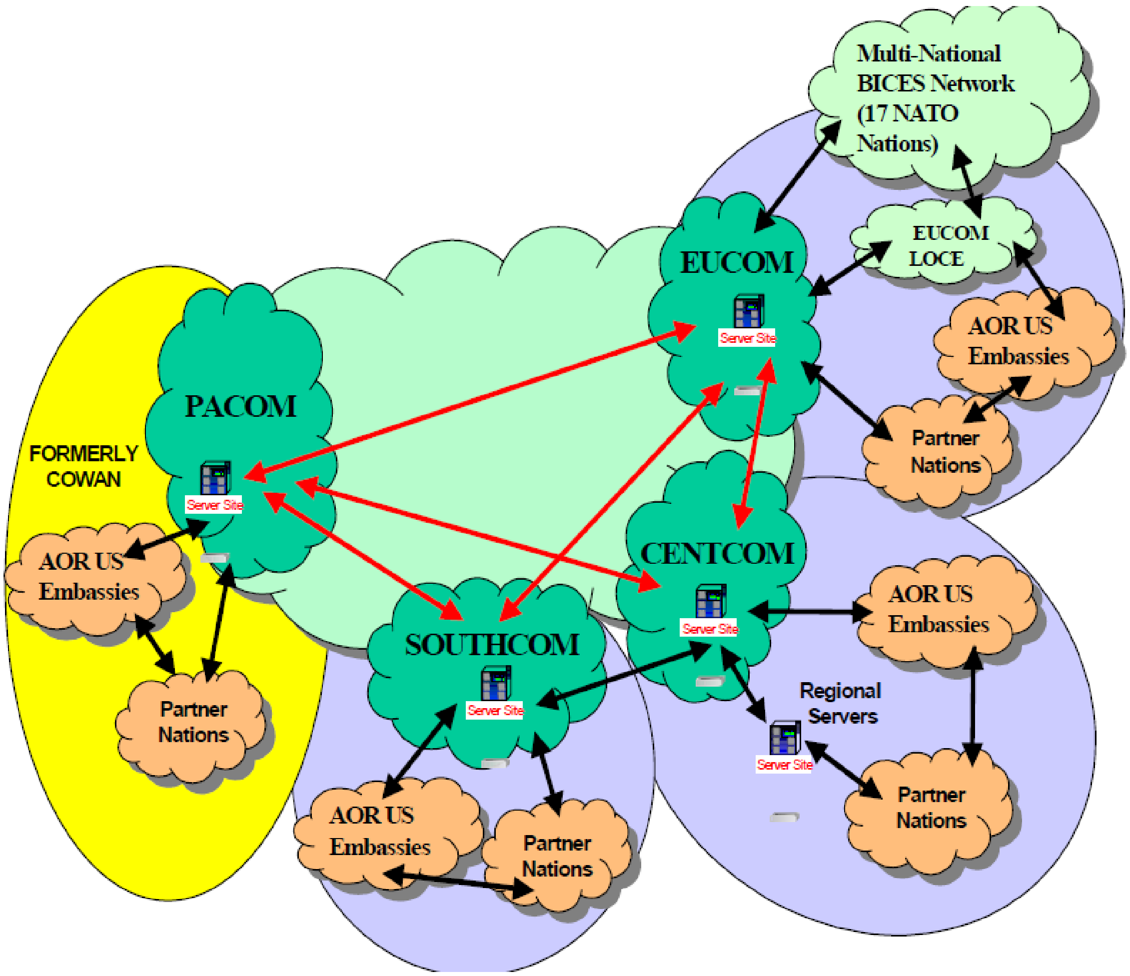

Figure 12. CENTRIXS architecture [From 24]

2. Commercial Shipping

a. Satellite – Inmarsat and iDirect

Inmarsat is a British Company that offers some of the most well-known commercial solutions for broadband communications at sea. These solutions can be used by a ship anywhere in the globe to connect to any shore network through the Internet. One of the commercial products Inmarsat is offering is FleetBroadband, which along with voice and SMS services, offers a 432kbps Internet and intranet connection through a secure VPN channel [26], [27].

iDirect is another Company that provides maritime communications solutions. Their services have the Automatic Beam Switching feature, which seamlessly performs a handoff from one satellite beam to another as the ship moves, as well as a Group Quality of Service, which prioritizes traffic not only for individual applications or users on a specific vessel, but also manages the available bandwidth across the fleet [28].

b. Satellite - MCP

MCP Company has implemented a way to bring cell phone and Internet connectivity while at sea, even when there is no contact with regular terrestrial base stations. Their implementation includes ship-board antennas and base stations, which are connected to the ship's VSAT (Very Small Aperture Terminal) satellite system. Since a ship moves with the water and, in order to keep the VSAT pointing to the geostationary satellite, the antenna needs to be stabilized. Then over a satellite communications channel, the voice and data connections from the phones are routed from the ship to the shore gateway and then to the land network. GSM and CDMA phones are supported; the on-ship cellular network appears to the subscriber as a visited network; and the registration/billing process is handled through roaming. Also, the on-ship cellular network is automatically turned off as the ship approaches the shore to prevent interference with the relevant country's own cell networks, as transmission would only be allowed in international waters.

MCP's implementation also provides Internet connectivity while at sea, using WiFi antennas can be installed throughout the ship. Passengers and crew using their laptops or smartphones can connect to the ship's WiFi network using the browser, and then a captive portal handles the registration process and billing [29], [30].

c. WiMAX - Singapore's WisePort

WisePort, standing for WIreless-broadband-access at SEaPORT, is a project offering wireless broadband connectivity to Singapore's coastal waters, up to a range of 15 km (about 8 nautical miles). Its trial started on March 2008 and its commercial launch took place on March 2009. It was implemented using a mobile WiMAX wireless broadband network, created by 6 WiMAX base stations along the shoreline, and initially offering a 512 kbps up to 8Mbps unlimited data access plan. The WisePort project enabled ferries, arriving and anchored vessels to access the Internet to send engine reports to shore, receive schedules and instructions, submit digitally any necessary documents to the terminal operators, contact their logistics providers, access tidal information and receive electronic chart updates. Islands and offshore oil platforms are also potential customers to the system. Aside from Internet access, they can implement a remote live video surveillance security system and access their company's databases.

As a much cheaper, faster, more efficient and more reliable alternative to satellite communications, WisePort had 250 subscribers even before its official launch. Its cost was 12 million Singapore dollars (about $8 million) [31], [32], [33].

d. WiMAX and WiFi - Seattle ferries

The U.S. Department of Transportation funded the Washington State Ferries Wireless Connection Project (WSF WCP) [34]. The project was to provide a seamless 802.11 wireless connectivity to passengers waiting on the ferry terminals and aboard the ferries while in transit. The contractor was Mobilisa, Inc. and it installed WiFi directional antennas on specific shore sites and onboard the ferries. The connection was then routed to the ferry's onboard 802.11 access point. As shown in Figures 13 and 14, they managed to cover a range up to 5 miles, while the ferry routes length vary from 2.8 to 15.5 miles [35], [36]. This project shows that even WiFi can be used to connect ships traveling near the coast.

Six years later, in 2009, WSF contracted with Proxim Wireless, Inc. to upgrade the network using WiMAX point-to-multipoint antennas that would provide over 12Mbps throughput to each ferry, as well as 11 ferry terminals [36]. There were reports, however, that Proxim experienced difficulties with interference caused by the scattering of the wireless signal, as the water acts as a mirror for these signals. The company had to install a greater number of shore antennas to improve the reliability of the network [38]. Proxim's equipment were used later in 2010 in San Francisco Bay, where they implemented a WiMAX network for providing a 12Mbps to 36Mbps connection speed to commercial vessels covering all of the bay area, about 62 square miles. Additionally, they provide a WiFi connection to recreational vessels that are closer to shore, up to 0.5 mile [39].

Figure 13. WSF Ferry routes

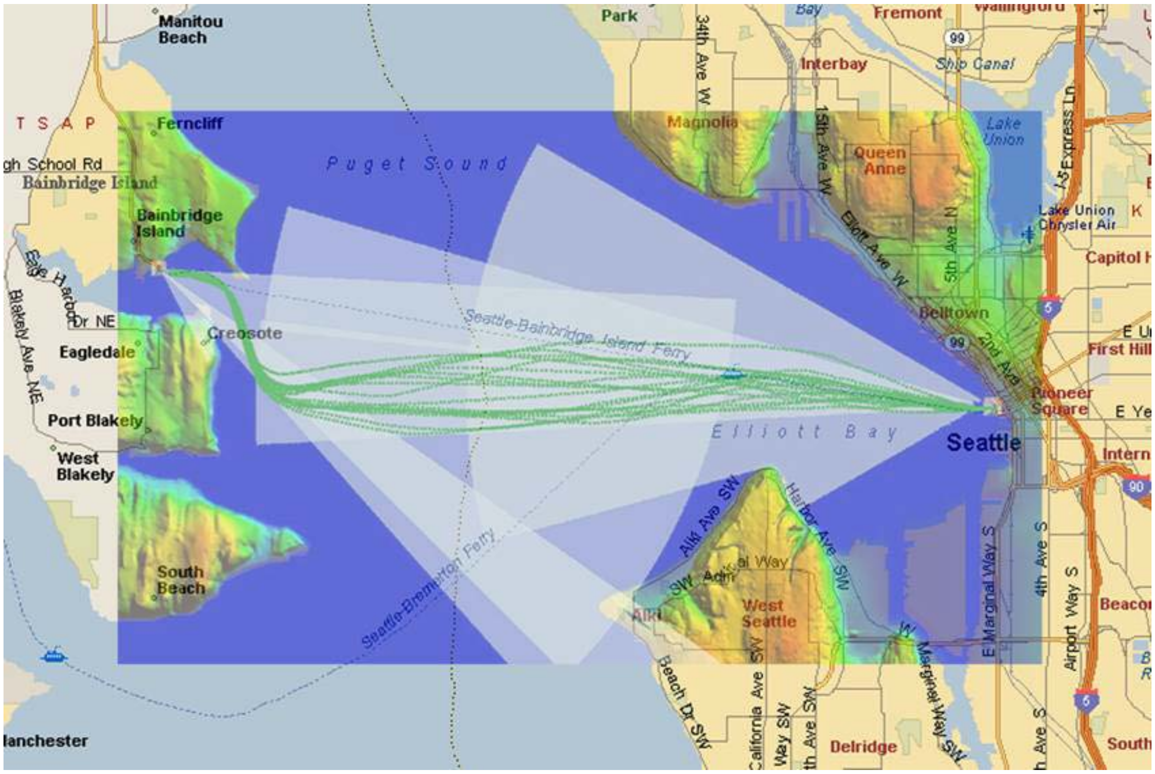

Figure 14. WiFi coverage of Seattle-Bainbridge ferry route

e. 2G/3G cellular Networks

Ships that are near the coast may have the option of accessing a commercial land-based 2G or 3G cellular network for their voice and data communications. If the ships operate in multiple countries, however, additional roaming charges may apply that can be comparable to the cost of a satellite link.

3G is usually limited to a line-of-sight range. That said, 2G range in some conditions can be even greater than WiMAX, up to 30 miles or more, depending on the height of the cell tower from sea level and the use of directional antennas. Of course, a 2.5G GPRS data connection is not considered broadband, especially compared with the latest wide-area cellular networks. Maximum available bandwidth for a single GPRS connection would be about 150Kbps, so its bandwidth is comparable to an ISDN line. It's still a cheap and efficient solution compared to a satellite link, depending on the ship's bandwidth needs.

In some areas in the world, like in the Aegean Sea, the islands scattered throughout the region can uniformly cover a very large area. As shown in the following images, taken from one of Greece's major cellular providers, the 3G network covers about 90% of the Aegean (without specifying, however, the actual available bandwidth). 2G coverage exists almost everywhere. So a ship, for example, traveling through the Aegean Sea to the Black Sea would almost always have at least 2G connectivity (a distance of about 300 nautical miles).

Figure 15. 2G network coverage in Greece [From 40]

Figure 16. 3G network coverage in Greece [From 40]

C. SHORTFALLS AND USEFULNESS

Connecting a ship to a shore network continues to be a major issue, both for military and commercial applications. A Navy warship, by being able to communicate with its HQ shore network can send reconnaissance photos, exchange documents, send logistics requests, or even use VoIP and videoconferencing applications if a broadband connection is established. Commercial vessels can connect to their company headquarters and request technical manuals and updated electronic maps, send up-to-date loading manifests, and increase their crew morale by providing them an Internet connection for their private needs.

Satellite communications has been the solution to cover these needs. Apart from being expensive and slow, however, satellite communications have a great impact on the performance of TCP. In satellite communications, the propagation path would be from the ship to the satellite, then from the satellite to the shore station, and back again. A geostationary satellite (GEO) orbits the earth at an altitude of 35,786km. As a result, the additional propagation delay when using a GEO would be

$$t_{prop} = \frac{4 \times 35.786 \times 10^3 \, m}{3 \times 10^8 \, m/sec} \approx 0.5 \, sec.$$

This round trip time (RTT) of 500ms, results in a very large Delay × Bandwidth product. Since the largest TCP window size without options is 65,535 bytes, the satellite connection throughput would be limited to 1Mbps per connection, thus underutilizing the channel [43]. Transmission errors caused by atmospheric or electro-magnetic interference will also negatively affect throughput, as the TCP sender would assume that there is network congestion and as such enter a network congestion avoidance state. There have been workarounds implemented to these problems though, such as the slow-start algorithm, large window sizes and delayed ACKs, along with forward error-correction (FEC) techniques to reduce the overall bit error rate (BER).

Alternative solutions to the expensive and usually slow satellite communication channels are the cellular networks, WiMAX 802.16 and even Wi-Fi 802.11. Their availability, however, is limited to coastal waters. Among these solutions, WiMAX offers higher peak data rates, higher average throughput and various levels of QoS. WiMAX, however, was designed as a fixed system, while the 2G and 3G cellular protocols were designed for mobility, including transfer of mobile users from one cellular network to another. The latest 802.16m release (also known as WiMAX 2), approved by IEEE on March 2011, however, supports data rates up to 100Mbps for speeds up to 500km/h. Generally, however, WiMAX compared to 3G and Wi-Fi lies somewhere in the middle in terms of data rate, coverage range, mobility and overall cost. These facts will be taken into account in the experiment setup outlined in the Chapter III.

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III. EXPERIMENT DESCRIPTION

A. MOTIVATION

Each of the four connectivity methods for a ship, WiMAX, 2G/3G Cellular, wave relay and satellite communications, has advantages and disadvantages as described in Chapter II. Obviously, the first differentiating characteristic between them is the overall cost, which includes the purchasing and installation of the required hardware, radios or antennas, as applicable for each case, as well as the cost of using these links. These connectivity methods, however, also offer different levels of bandwidth, Quality of Service (QoS) and operational range. In the following experiment, it will be shown how bandwidth and latency are affected as a ship is moving away from shore, approaching each method's performance range limitations.

B. GEOGRAPHY

The experiment takes place in the Monterey Bay area, as shown in the following figure, and consists of two main parts. In the first part, the experiment is conducted alongside the bay's shoreline, starting from Monterey and moving northwards to Santa Cruz, following California Highway 1. A WiMAX and a wave relay radio are set up on top of Spanagel Hall on the Naval Postgraduate School campus. These radios, serving as the master access point, respectively, have 120-degree sector antennas. The radios on the mobile end of the links have omni-directional antennas, as the purpose of the experiment is to show the possibilities for connectivity of a moving ship, and if directional antennas were used they would have to be constantly adjusting the ship-borne antenna bearing according to the ship movement. Firstly, an initial testing of the equipment from within NPS is performed, which also serves as a "best case" scenario. Then, the drive moves from Monterey towards Santa Cruz, increasing the distance between the mobile terminal and the base radios, and conducts measurements related to the network's performance. The bay's curving shape also ensures that the radio signal will propagate over the ocean, which impacts the network's performance, as the radio waves "bounce" off the water.

The limitation to this part of the experiment is that measurements can't be taken for 2G/3G cellular connectivity, as the moving is not far enough away from the cell towers.

Figure 17. Initial equipment test within NPS – "Best case"

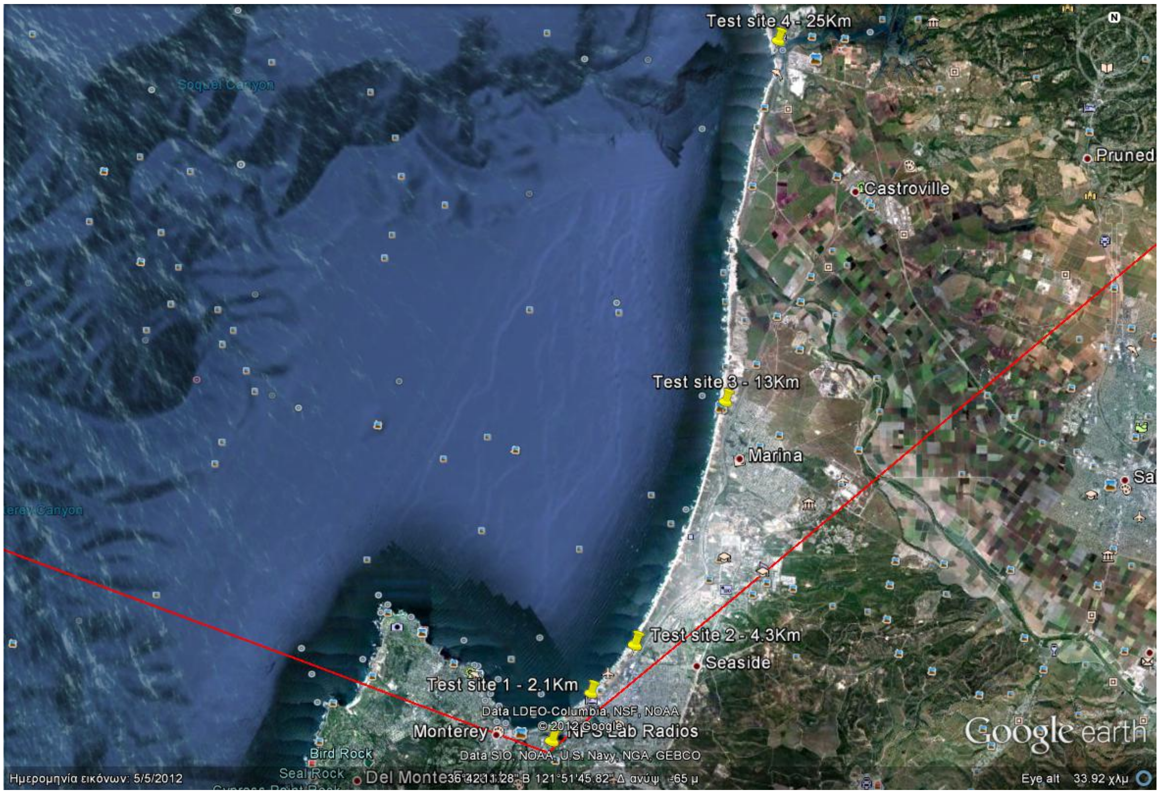


Figure 18. Test sites on Monterey Bay coast

In the second part of the experiment, the required equipment is loaded on a boat and as the boat starts moving away from the shore, measurements are taken on how each connection method performs at the designated waypoints. These waypoints are shown in the following figure, and are selected in such a way that the distance increases from the base WiMAX and wave relay radios, as well as from the commercial cellular towers on shore. It should be noted that the distance for each of the waypoints from the WiMAX and wave relay radios is always precisely known, but the exact distance from the cellular tower is not known. This is because the precise cellular tower coordinates are unknown. Another unknown is which cellular tower the mobile terminal is connected to at each time. Thus, in the range calculations it is assumed that the cellular tower is located at the closest point to the shore. All of the waypoints also have a direct line-of-sight connectivity to the base radios, with no physical obstacles in between, ensuring an optimal connectivity configuration. The only exception to this is the tree line between NPS and the beach (by Del Monte Ave), which might impact the performance measurement.

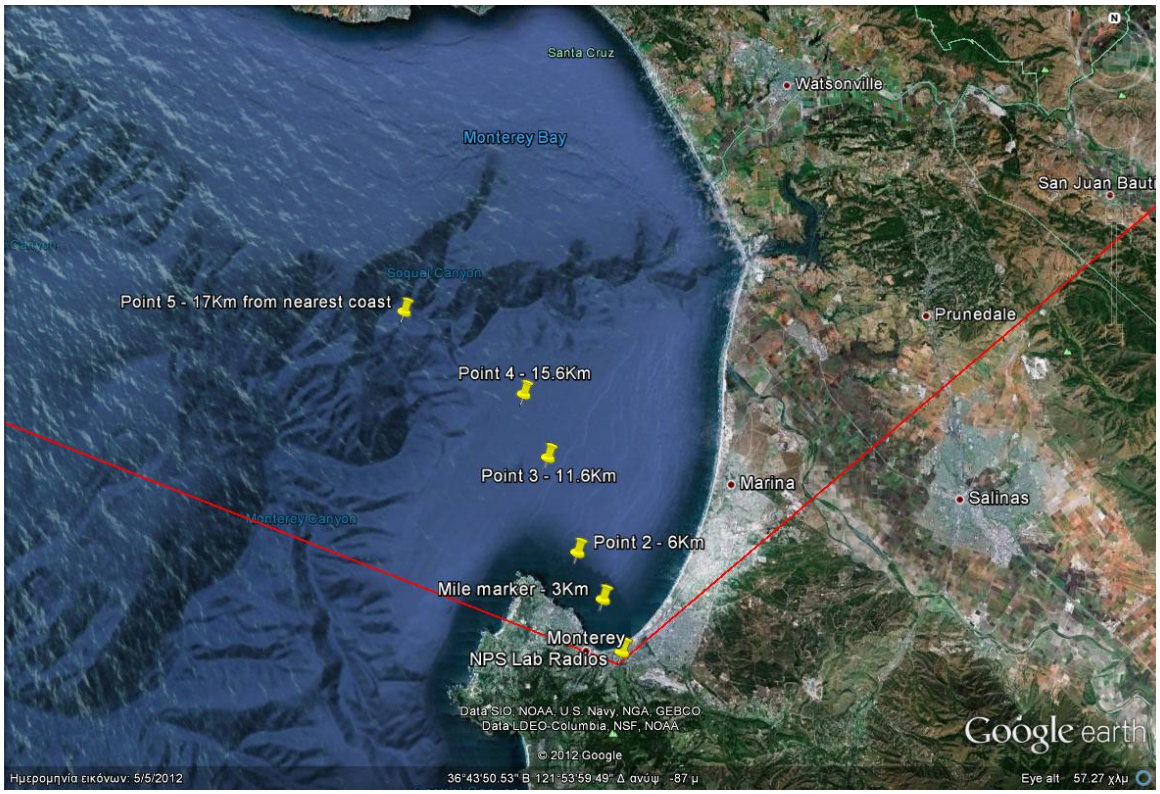


Figure 19. Waypoints for sea testing

C. ARCHITECTURE

The experiment's architecture is depicted in Figure 20. This architecture is divided into 2 main parts: the reception side, located on the mobile terminal (on the car or on the boat), and the laboratory side, located at the Naval Postgraduate School.

For the reception, or mobile, side of the experiment, a laptop can be connected to one connection path at a time. In the fixed side (laboratory space in NPS), there is a laptop that is directly connected to the WiMAX and Wave Relay radios using an Ethernet switch and CAT5 Ethernet cable. To achieve connectivity with the mobile terminal using cellular and satellite networks, the server is also connected to the Internet using an NPS gateway, allowing ports 80, 441 and 5001 through NPS's firewall. Access to these ports is being forwarded to the experiment's server.

The WiMAX and Wave Relay radios belong to NPS's internal private network, since they don't need to communicate with the outside world. The address space the experimenters chose for them is 172.26.51.0/24, with the specific IP addresses shown in the diagram.

The server is running the "iperf" bandwidth measurement tool in server mode (terminal command: iperf –s) and listening on the default port 5001. The server also runs TeamViewer, a remote control and desktop sharing software under a free non-commercial license. This software needs ports 80 and 441 to function [46], and provides the ability to remote control the server's desktop on Spanagel Hall's rooftop from the remote location. Note that this requires Internet connectivity from the remote location to work, so the 2G/3G cellular data link will also be used for this purpose.

The mobile client runs iperf with the following options, depending on whether the choice is to transmit a fixed-size file or for a specific amount of time (for the experiment, it was set for 10 seconds):

```
iperf -c <server IP address> -P 1 -i 1 -p 5001 -f k -n <filesize>
```

or

```
iperf -c <server IP address> -P 1 -i 1 -p 5001 -f k -t 10.
```

The –P 1 option allows only one parallel client thread to run; the -i 1 option reports the bandwidth measurements at 1-second intervals; the -p 5001 option sets the connection port to 5001; and the –f k option sets the reporting format to Kbits/sec.

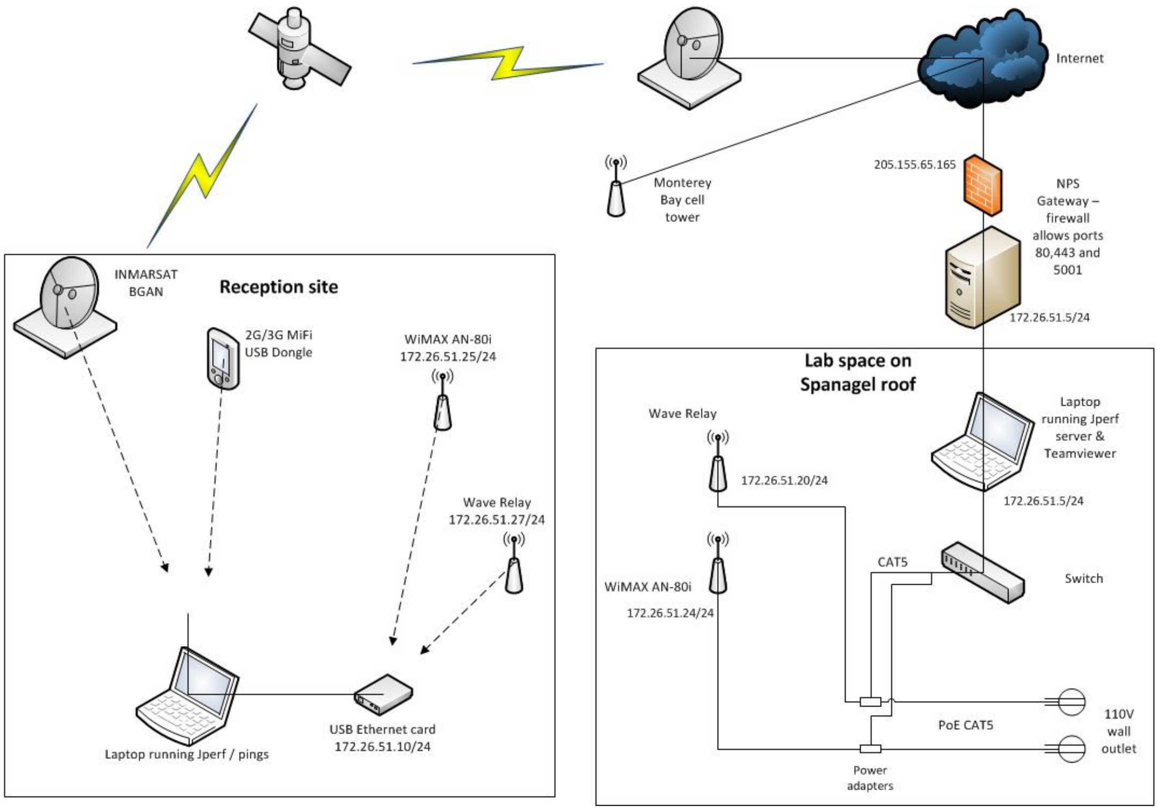


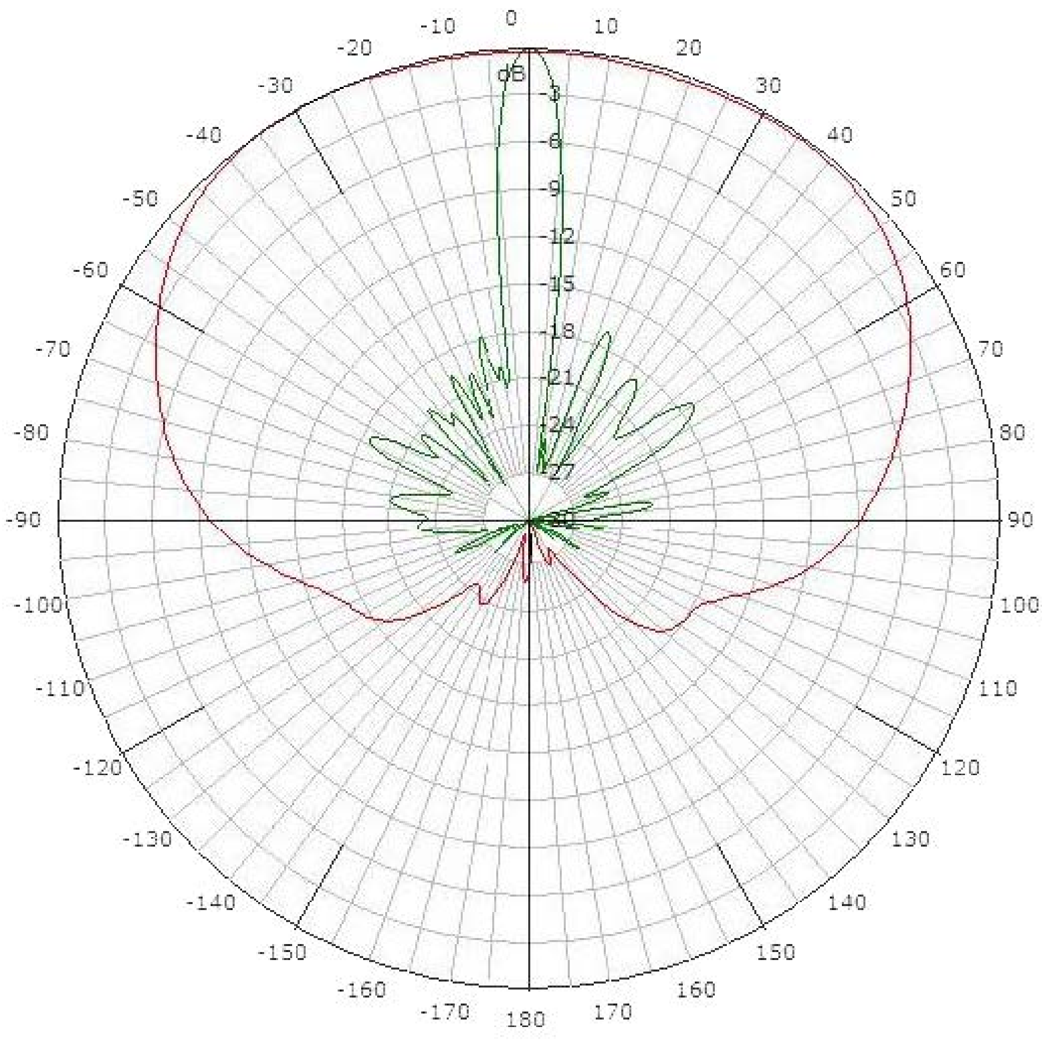
Figure 20. Experiment architecture

D. HARDWARE SPECIFICATIONS

1. WiMAX Radio and Antennas

For communicating using IEEE 802.16 WiMAX, two (2) identical AN-80i Radio Platforms were used, both of which were manufactured by Redline ® Communications. For this experiment, these radios were operated in the Point-to-Point communication mode, using the 5.8 GHz frequency band. According to the manufacturer’s datasheet, it can achieve a range of over 80 kilometers (50 miles), and it can deliver up to 90Mbps [48]. Notable specifications for the AN-80i are AES-128 and AES-256 encryption options, up to 40 MHz channel size, and 25dBm maximum transmission power (just less than 400 mW). For on-site deployment purposes, it requires an 110V/220V power supply for a Power over Ethernet (PoE) injector and a maximum of 300ft CAT5 Ethernet cable. It weighs 2 kg (4.5 lbs.).

The antenna used is a SA58–120–16-WB 120-degree, vertically polarized, sector antenna manufactured by Laird technologies. Its sector covers Monterey Bay as well as the coastal areas, as depicted on Figure 21. The antenna is weatherproof, has a 5470 - 5850 MHz frequency range, 16 dBi Gain and weighs 1.2 kg (2.6 lbs.). Its gain pattern is depicted on the following figure, where the purple line defines its gain horizontally and the green line defines its gain vertically. It should be noted that its vertical beamwidth is only 7 degrees, so the antenna installation must be precise enough to ensure optimum performance.



SA58–120–16-WB antenna gain pattern[From 49]

For the slave (mobile) terminal, an ODN9–5725 omni-directional antenna is used, manufactured by Mobile Mark, Inc. The experimenters prefer using an omni-directional antenna over a sector or directional antenna, since in the sea phase of the experiment, the boat changes its heading at all times, and also pitches and rolls from the ocean waves. The antenna has a 5.72–5.83 GHz response range, 9 dBi gain, and weighs less than 1 lb. [55].

2. Wave Relay Radio and Antennas

For Wave Relay communications, two (2) identical Wave Relay WR-RTR2 Quad Radio Routers are used, manufactured by Persistent Systems, LLC. These radios can operate in the 2.3 – 2.5 GHz frequency range (S-Band) and 5Ghz (C-Band). For testing purposes, the S-Band frequency range is used. According to the manufacturer's website, it has a range of more than 2 miles using an omni-directional antenna, and a 27Mbps maximum throughput on TCP and 37Mbps on UDP, using a 20MHz channel. Notable specifications for the WR-RTR2 are AES-CTR-256 bit encryption with SHA-512 MAC, 600 mW transmission power (military version has 2 Watt transmission power which doubles the range) and up to 40MHz channel size. Similar to the AN-80i, it needs an 110V/220V power supply for a Power over Ethernet (PoE) injector. It weighs 3.2lbs. [50], [51].

Figure 21. Wave Relay WR-RTR2 Quad Radio Router installed on Spanagel Hall rooftop, Naval Postgraduate School

The antenna used at the lab site is an HG2414SP-120 120-degree, vertically polarized, sector antenna manufactured by L-com. It points to the exact direction as the antenna for the AN-80i to achieve comparable results in the experiment. This antenna is similar to the SA58–120–16-WB, except it's operating within the 2.4 GHz ISM band. It has a gain of 14 dBi and weighs 2 kg (4.4 lbs.). Its gain pattern is depicted by Figure 7. Its vertical beamwidth is 15 degrees (compared to 7 degrees for the SA58–120–16-WB). The mounting system for this antenna is also more stable and heavy-duty, only adjusting from 0 to 20 degrees down tilt. For the experiment's purposes, the antenna is mounted at 0 degrees vertically, since the expected operating range will need it to be pointing to the horizon.

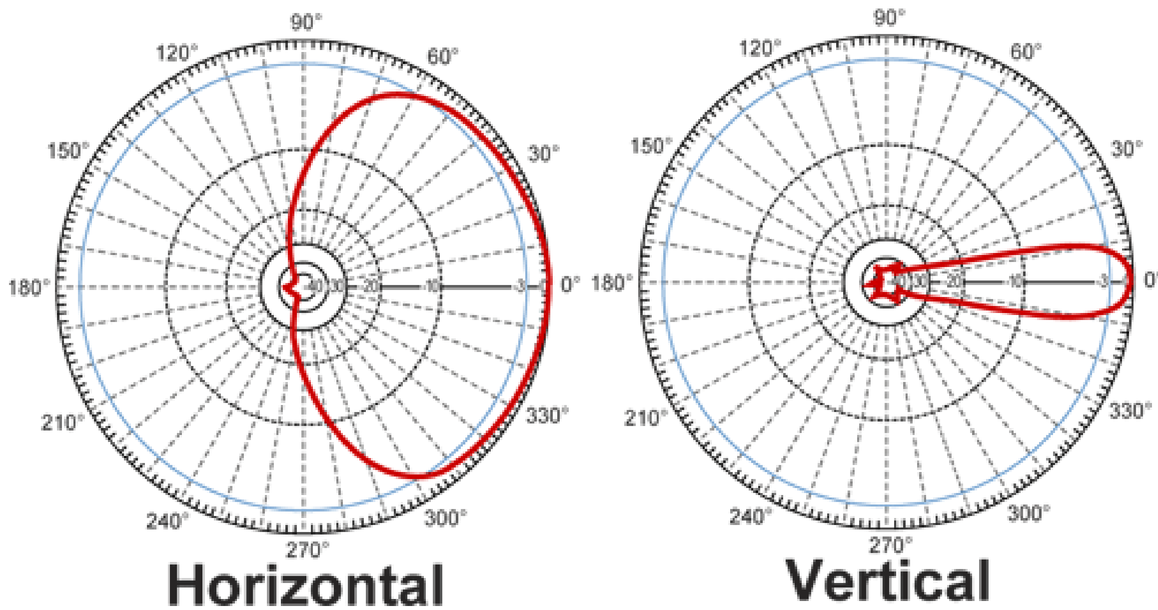


Figure 22. HG2414SP-120 antenna gain pattern

The slave (mobile) antenna for the Wave Relay link is an OD24M-5 omni-directional antenna, manufactured by Laird technologies. It has a 5 dBi gain, operates in the 2400–2485Mhz band, and weighs 0.2 kg (0.5 lb.) [56].

3. 2G/3G Cellular Device

To test 2G/3G cellular communications, an AT&T Mobile Hotspot MiFi® 2372 is used, manufactured by Novatel Wireless. This device supports tri-band HSUPA/HSDPA 7.2 operating at 850, 1900 and 2100 MHz, and quad-band GPRS/EDGE operating at 850, 900, 1800 and 1900 MHz. It can connect to the experiment's testing computer using either 802.11b/g or USB, and it can be battery or USB-powered. The device itself is very small and light, weighing only 3 ounces [53].

Figure 23. AT&T Mobile Hotspot MiFi® 2372

4. Inmarsat Broadband Global Area Network (BGAN)

For satellite communications testing, this thesis' equipment is a Hughes 9450 BGAN (Broadband Global Area Network) Mobile Satellite Terminal. According to its manufacturer, it has a maximum throughput of 464 Kbps while on-the-move. An autonomous tracking antenna acquires and tracks the BGAN satellite. The transceiver weighs 2.3 kg and the antenna weighs 2.0 kg. It requires a 12V or 24V DC input voltage. Like the 2372 MiFi, it can connect to this experiment's testing computer using an 802.11 connection [54].

Figure 24. Hughes 9450 BGAN Mobile Satellite Terminal

5. Client and Server Laptops

The experiment’s server laptop is a Dell Latitude E6500, with an Intel Core 2 Duo P9500 processor running at 2.53 Ghz, 4 GB RAM, and 200 GB hard disk. It is connected through the built-in Intel 82567LM Gigabit LAN interface. It runs Ubuntu 11.04 64-bit with no additional background running processes, except iperf server and TeamViewer.

The client's (mobile) laptop is a Dell Latitude E6410, with an Intel i7 M620 CPU running at 2.67 Ghz, 8 GB RAM and 500 GB hard disk. It has dual-boot OS capability, running either Windows 7 64-bit or Ubuntu 12.04 64-bit. The Ubuntu installation is clean with no background running processes, and that is used for this experiment's testing purposes.

Both laptops have iperf version 2.0.5 and TeamViewer version 7.0.9360 64-bit. The client's laptop also has Google Earth 6.2.2.6613 to keep track of test site locations.

6. Spectral Analyzer

To keep track of any existing interference at the test sites, an Anritsu MS2721B handheld is used. It is a battery-operated spectrum analyzer. It weighs 3.1 kg (6.9 lbs.) and can measure frequencies from 9 kHz up to 7.1 Ghz [57].

Figure 25. Anritsu MS2721B Handheld Spectrum Analyzer

E. PHYSICAL SETUP AND CONNECTIONS

The Wave Relay and WiMAX radios and antennas are installed on a pole on Spanagel Hall rooftop, at the Naval Postgraduate School. The actual setup is shown in the following picture. The radios are powered by 40 ft PoE cables, connected to the respective power adapters located in the lab space below. In that lab space, a laptop is installed to act as the iperf server, and a switch to connect the CAT5 cables from the radios and from the off-campus data link.

Figure 26. WiMAX and Wave Relay Master radios on Spanagel Hall roof, Naval Postgraduate School

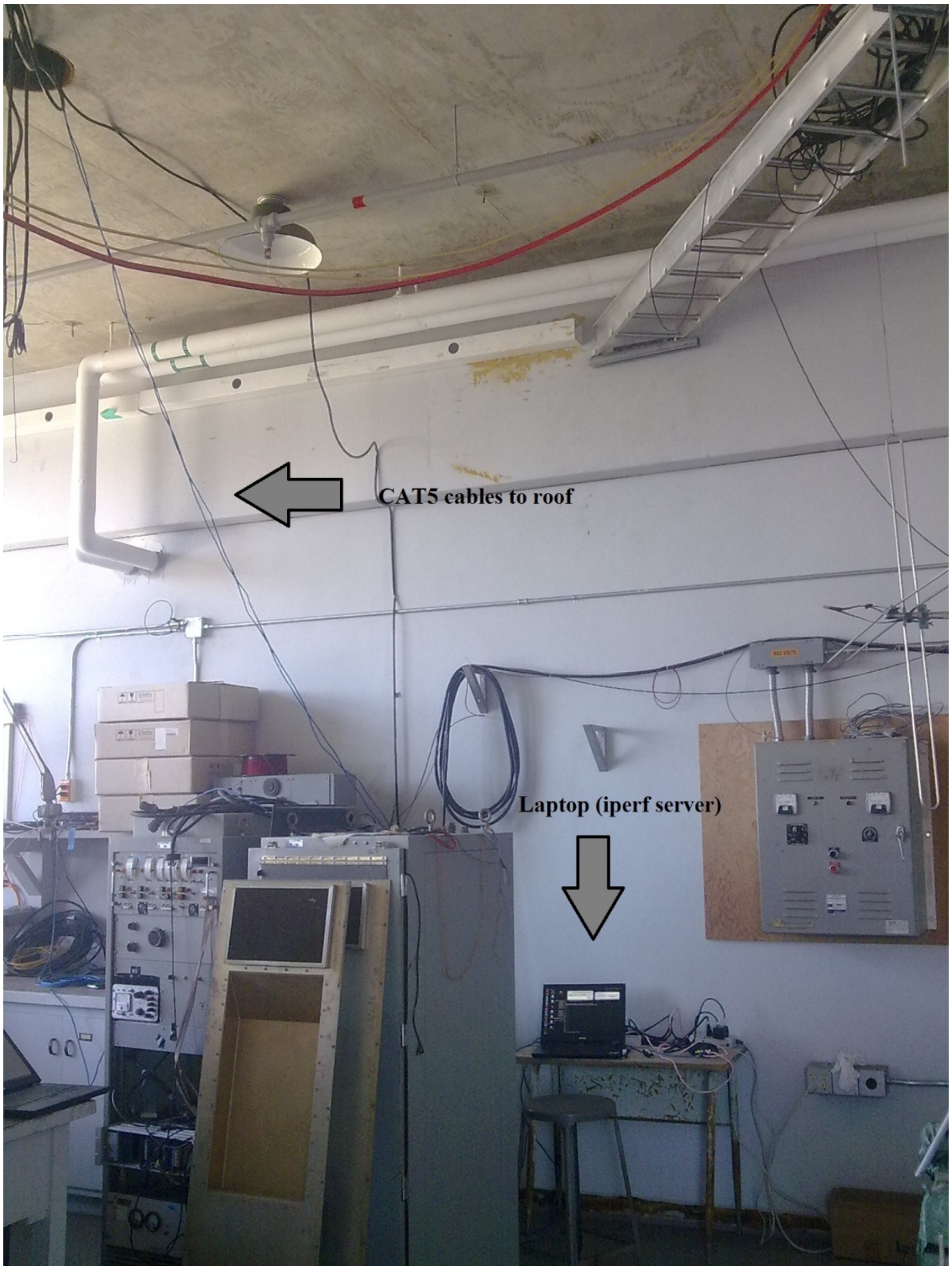


Figure 27. Laboratory space on Spanagel Hall roof

During the land-based phase of the experiment, a heavy-duty tripod is used to mount the radios for the remote (mobile) client. A 12V DC to 120V AC car power inverter was used for the necessary power supply for the radios' Power over Ethernet (PoE) adapters and the switch.

Figure 28. Wave Relay radio on the tripod at the Marina beach test site (labeled test site 3 on the map).

For the sea-based phase of this experiment, the radios are mounted on top of the boat's mast, as depicted in the following figure, to achieve the best possible line-of-sight range. The boat's on-board generator provides the necessary 120V power supply.

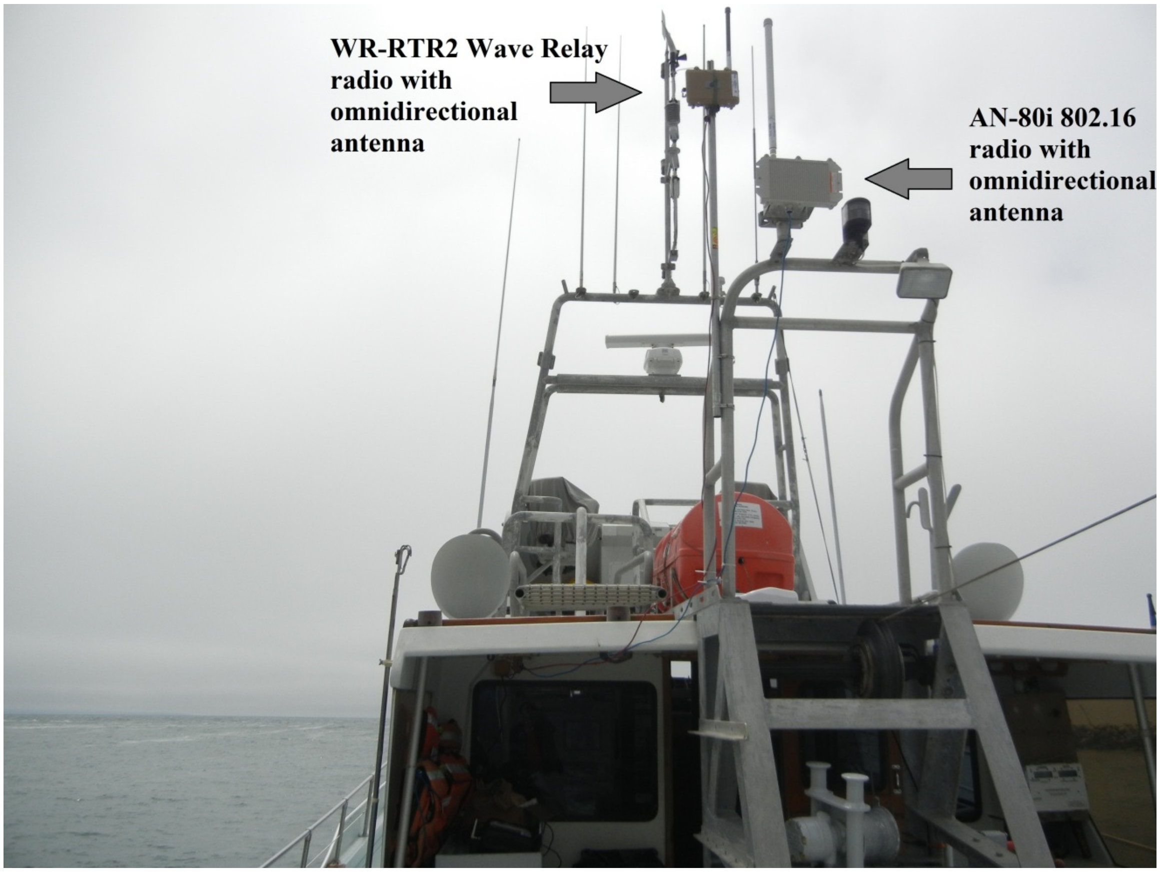


Figure 29. WiMAX and Wave Relay radios mounted on the boat's mast

F. EXPERIMENT PROCEDURE

Throughout the experiment, a TeamViewer is used to remote control the server, through which the transmission for the radios connected to it is turned on and off and their configuration is changed as necessary. The experiment procedure is as follows:

1. The WiMAX and Wave Relay radios in the laboratory site are connected to the power outlet and the laptop (running JPerf server), in accordance with the safety precautions.

2. After all necessary connections have been completed, the radios' transmission is disabled through their web interface and the laboratory area is left, ensuring that the remote desktop software is up and running.

3. The experimenters then go to the reception site (shore or ocean) at 1st waypoint (closest to NPS) and set up the remote radios.

4. Using either 2G/3G or Inmarsat connection, the server's desktop is connected and the appropriate radio's transmission is turned on for testing.

5. The corresponding remote radio is turned on, and bandwidth and latency is measured to the server by executing a script (described later), which runs iperf and ping commands several times.

6. Repeat steps 3 – 5 for the other connectivity methods as needed.

7. Move to 2nd waypoint, which is further away.

9. Repeat above steps until WiMAX, Wave Relay and cellular signal is lost.

9. Experiment complete – turn off lab radios remotely, then enter lab area, disconnect power supply and break down the equipment.

After the experiment is complete, the gathered data is gathered and analyzed. The result is identifying the most desirable method of connectivity to the shore for each case, based on the available bandwidth and latency, and taking into account the overall cost for each method.

G. TESTING SCRIPT

The iperf tool has a graphical frontend, written in Java, called Jperf, and can be downloaded from http://sourceforge.net/projects/jperf/. This GUI implementation for iperf, however, does not have the option for batch execution of measurements. For this experiment's purposes, iperf needs to be run multiple times to get an accurate average bandwidth measurement for each of the test sites. In addition, Jperf does not offer any option for data collection and analysis, as the user has to copy them to a text file and process them manually, which can be a time-consuming and exacting process.

To overcome these problems, the following two scripts are implemented, one for Microsoft Windows and one for Linux Operating systems, which can be used for this purpose.

1. **MS Windows Script**

```
@REM change to iperf path
@cd /
@cd <path to iperf executable>

@REM initial quick test of bandwidth
iperf.exe -c <IP address> -P 1 -i 1 -p 5001 -f k -t 10

@REM initialize loop variable
@SET /a i=1

:loop
@IF %i%==30 GOTO END
@echo Iteration %i%.
@REM run iperf to server transferring a 1MB file 30 times
iperf.exe -c <IP address> -P 1 -i 1 -p 5001 -f k -n 1000000 >> results.txt
@SET /a i=%i%+1
@GOTO LOOP

:end

@REM run iperf to server transferring a 10MB file
```

```
iperf.exe -c <IP address> -P 1 -i 1 -p 5001 -f k -n
10000000 >> results.txt


@REM run iperf to server testing bandwidth for 30
seconds
iperf.exe -c <IP address> -P 1 -i 1 -p 5001 -f k -t 30
>> results.txt


@REM ping server 30 times
ping -n 30 <IP address> >> results.txt


@move results.txt <path to desktop>
```

This script first does a 10-second initial test of bandwidth; then runs iperf to the server transferring a 1MB file 30 times; then a 10MB file once, then tests the bandwidth for 30 seconds and finally pings the server 30 times. All of the results are stored in a file called "results.txt" on the Desktop.

This simple script is not very useful because of the limited functionalities of Window's commands. The user needs to manually change the target IP address (for testing WiMAX and Wave Relay, it should be 172.26.51.5, the server's private IP address; for testing 2G/3G and satellite, it should be 205.155.65.165, the server's public IP address). It does not provide any data processing. Most importantly, if the available bandwidth is too low, then the measurement time can be very long, which would have an impact particularly on the sea testing phase of the experiment. To overcome these limitations, a more powerful script for a Linux environment is used.

2. Linux Script

The variables used in the following script are:

avgbw: total average bandwidth

bw: average bandwidth for each iteration, taken from ipef's output

bwsum: used for average bandwidth calculation

filesize: file size (in bytes) to be transferred by iperf

iperfile: the file name the user selects for output

iter: string containing iperf's output

iterations: number of times to transfer the file

n: bandwidth in Kbps, used for initial bandwidth test

userchoice: the user's menu selection

```
#!/bin/bash

#outside IP address 205.155.65.165
#internal IP address 172.26.51.5

filename="iperfile"; #default output file name
```

```
    while : #User menu
     do
        clear
        echo “-------------------------------------------”
        echo “Iperf network bandwidth measurement script”
        echo “-------------------------------------------”
        echo “[1] Test WiMAX or Wave Relay”
        echo “[2] Test 2G/3G or Satellite”
        echo “[3] Select output filename”
        echo “[4] Exit”
        echo “=======================“
        echo -n “Enter your menu choice [1–3]: “
        read userchoice
        case $userchoice in

         1)   n=$( iperf -c 172.26.51.5 -P 1 -i 1 -p 5001
-f k -t 10 | tail -1 | awk ‘{ print $(NF-1) }’ ); #Quick
initial test of bandwidth
              echo  “Bandwidth: $n Kbits/sec”;

              bwsum=0; #Initialize value for bandwidth sum

              if ( [ $n -lt 100 ] ); then
                   echo “Bandwidth: Very low”;
```

```
          filesize=500000;
          iterations=10;



     elif [ $n -lt 500 ]; then
          echo “Bandwidth: Low”;
          filesize=1000000;
          iterations=10;

     elif [ $n -lt 1000 ]; then
          echo “Bandwidth: Ok”;
          filesize=1000000;
          iterations=30;

     elif [ $n -ge 1000 ]; then
          echo “Bandwidth: High” ;
          filesize=3000000;
          iterations=30;
     fi;

     echo “Testing $iterations times for a
$filesize byte filesize”;
     for ((m = 1; $m < $iterations + 1 ; m = $m +
1)) do
```

```
		echo “Iteration $m out of $iterations”;


		iter=$(iperf -c 172.26.51.5 -P 1 -i 1 -p
5001 -f k -n $filesize 2>&1 | tee -a $filename /dev/tty );
#pipe output to filename, to standard output and to
variable
		bw=$( echo “$iter” | tail -1 | awk ‘{ print
$(NF-1) }’ );
		echo “Bandwidth for iteration $m was $bw
Kbits/sec”;
		bwsum=$(($bwsum +$bw));
		echo “Bwsum is $bwsum”;
		done;
		echo “Bwsum is $bwsum”;
		echo “Iterations are $iterations”;
		avgbw=$(($bwsum / $iterations));
		echo “Average bandwidth was $avgbw” 2>&1 |
tee -a $filename;
		ping -c 10  172.26.51.5 2>&1 | tee -a
$filename;
		echo “Script date:” 2>&1 | tee -a $filename;
		date 2>&1 | tee -a $filename;
		exit 0;;
```

2) n=$(iperf -c 205.155.65.165 -P 1 -i 1 -p 5001 -f k -t 10 | tail -1 | awk ‘{ print $(NF-1) }’); #Quick initial test of bandwidth

```
echo  “Bandwidth: $n Kbits/sec”;

bwsum=0; #Initialize value for bandwidth sum

if  [ $n -lt 100 ]; then
     echo “Bandwidth: Very low”;
     filesize=500000;
     iterations=10;


elif [ $n -lt 500 ]; then
     echo “Bandwidth: Low”;
     filesize=1000000;
     iterations=10;

elif [ $n -lt 1000 ]; then
     echo “Bandwidth: Ok”;
     filesize=1000000;
     iterations=30;

elif [ $n -ge 1000 ]; then
```

```
			echo “Bandwidth: High” ;
			filesize=3000000;
			iterations=30;
		fi;

		echo “Testing $iterations times for a $filesize byte filesize”;
		for ((m = 1; $m < $iterations + 1 ; m = $m + 1)) do
		echo “Iteration $m out of $iterations”;

		iter=$(iperf -c 205.155.65.165 -P 1 -i 1 -p 5001 -f k -n $filesize 2>&1 | tee -a $filename /dev/tty ); #pipe output to filename, to standard output and to variable
		bw=$( echo “$iter” | tail -1 | awk ‘{ print $(NF-1) }’ );
		echo “Bandwidth for iteration $m was $bw Kbits/sec”;
		bwsum=$(($bwsum +$bw));
		echo “Bwsum is $bwsum”;
		done;
		echo “Bwsum is $bwsum”;
		echo “Iterations are $iterations”;
		avgbw=$(($bwsum / $iterations));
```

```
                echo "Average bandwidth was $avgbw" 2>&1 |
tee -a $filename;


                ping -c 10  205.155.65.165 2>&1 | tee -a
$filename;
                echo "Script date:" 2>&1 | tee -a $filename;
                date 2>&1 | tee -a $filename;
                exit 0;;



          3) echo "Please enter output file name:"
                read filename;;


          4) exit 0;;


          *) echo "Please select choice 1,2 or 3!";
               echo "Press a key..." ; read ;;


      esac
     done
```

The key differences in the above script compared to the MS Windows script are:

a. It has a user-friendly menu. It gives the option for the user to select a filename for storing the results, which is important for keeping track of the measurements collected for each of the test sites. Also, it provides the choice for testing WiMAX/Wave Relay or

2G/3G/Satellite, as the first group uses the private IP address and the second group uses the public IP address.

b. The quick initial test of bandwidth serves as a method to avoid excessive testing times. If the bandwidth is sufficiently high, then the script chooses to run more iperf iterations and larger file sizes, but if the bandwidth is low then the script runs less iterations for smaller file sizes to expedite the testing process.

c. The output is simultaneously printed to the terminal window and written to the output file, such that the user can keep track of the script's testing progress and be aware of any connectivity problems that might arise while testing. For example, the connection to the server can be lost during the testing process, and the user would not know about it if the results were only output to the file. This is accomplished by the "tee -a $filename /dev/tty" command, which pipes the output to the file (filename) and to standard output (monitor).

d. The average bandwidth of each iperf iteration is added to a variable, called "bwsum" and then the overall average bandwidth is calculated by dividing it with the number of iterations. By using the pipe commands " | tail -1 | awk '{ print $(NF-1)," the script stores the number of iperf outputs in its final result line to a variable.

e. Linux's ping command result is more descriptive by itself, providing a minimum, average, maximum, and standard deviation RTT value for all of the pings performed. This is especially useful for this experiment's purposes, since it will report any "latency spikes" that might happen, especially in the sea phase of the experiment.

For the above reasons, the experimenters prefer that the mobile client runs on a clean, freshly-installed Linux environment, that also ensures that the bandwidth measurements are as accurate as possible, without any processes running in the background (like automatic updates) that would skew the results. The next chapter provides the results of the field experiments and an analysis of those results.

IV. EXPERIMENT RESULTS AND ANALYSIS

A. FIRST PHASE OF EXPERIMENT – LAND-BASED TEST RESULTS

1. Initial Tests at NPS

The first step was to perform the initial testing of the WiMAX and Wave Relay connections, which also served as the "best case" scenario, as the distance between the fixed master radios on Spanagel Hall roof and the mobile radios in Glasgow Hall was only 450 meters, with no physical obstacles in between.

After setting up the tripod and making the necessary power and network connections, the first connections were to the fixed Wave Relay radio through the laptop server using TeamViewer to power it on and configure it. The settings chosen in the radio web interface are depicted in Figure 31.

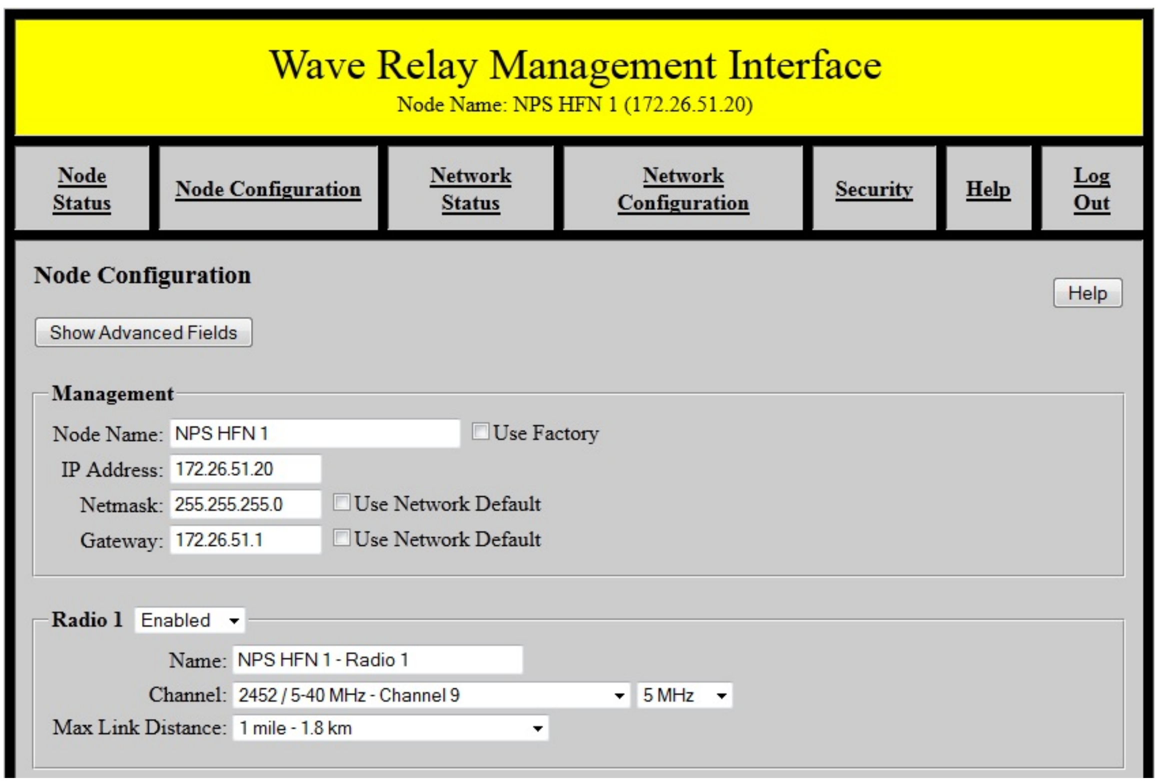


Figure 30. Wave Relay master radio configuration settings

The channel width was set to 5Mhz (maximum value is 20Mhz) and the maximum link distance to 1 mile, to minimize interference (minimum value is 0.2 miles). The mobile radio had the exact configuration. The AES-256 key in the security tab was set to the same value in both radios.

After running the Linux script, which runs iperf 30 times for a 3MB file, an average bandwidth of 4449 Kbits/sec was observed. The results have a standard deviation of 80, meaning that the available bandwidth was relatively stable. Latency measurements from pings averaged 5ms and stable.

Next, the Wave Relay radios were disabled and the WiMAX radios were powered. The master WiMAX radio configuration is depicted in Figure 32.

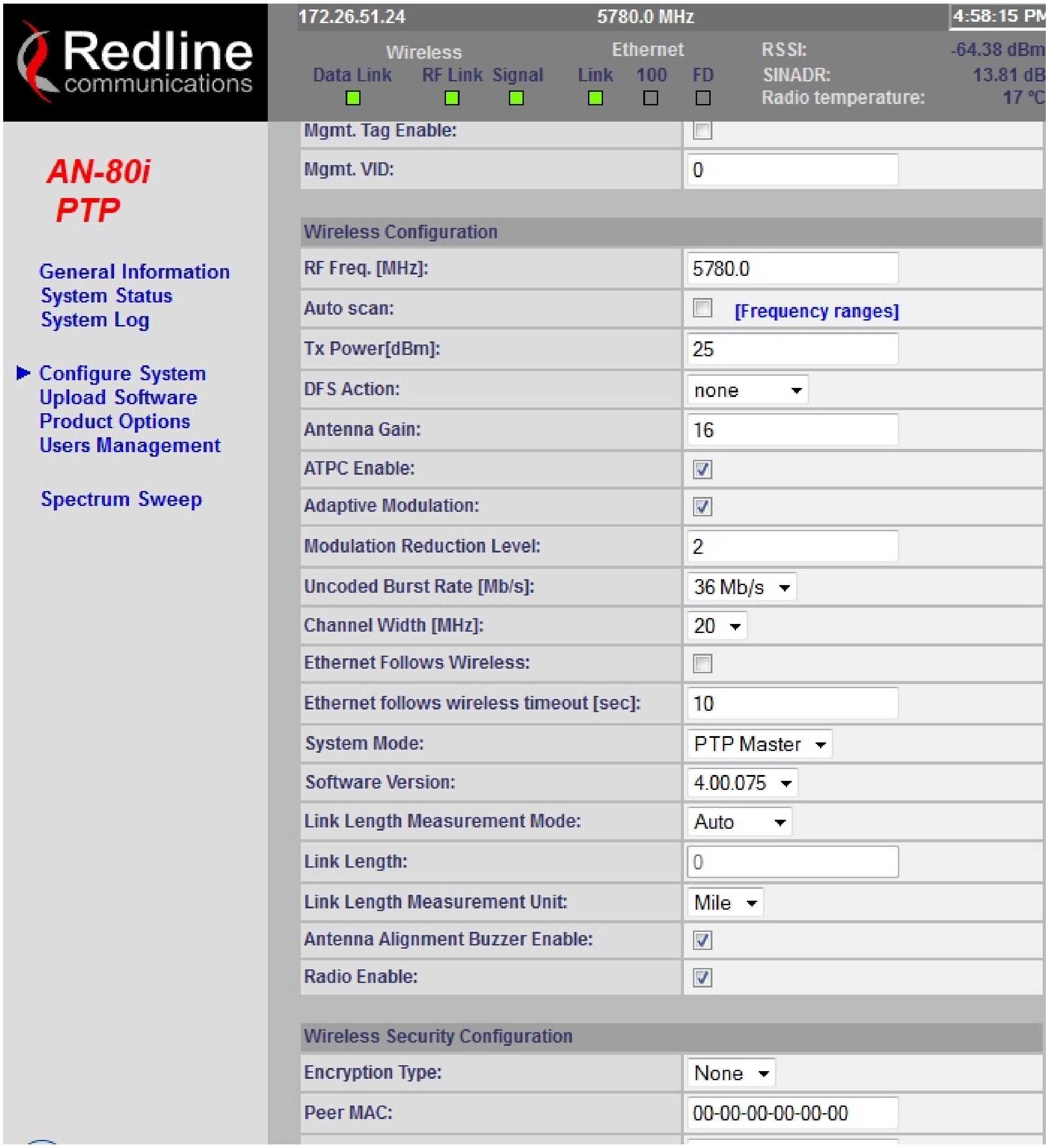


Figure 31. WiMAX master radio configuration settings

First, the transmit frequency was set to exactly 5800 MHz, but the radios could not connect to each other, so the frequency was lowered to 5780 MHz. The transmit power was set to maximum (25dBm or just under one-third Watt) because the signal to interference, noise and distortion ratio (SINR) was low (13.81dB at the master radio; 20.04dB at the mobile radio). Eventually, after some difficulties, the radios connected to each other and the experimenters began running the bandwidth measurement script. After transferring a 3MB file 30 times, an average bandwidth of 4350Kbps was observed, comparable to that of Wave Relay. The standard deviation, however, was 1060, much higher compared to Wave Relay, meaning that the connectivity fluctuated much more. In the detailed results file, the maximum bandwidth for a 1-second interval was found to be 8300Kbps, but the minimum is zero (meaning that the radios for some time slots were not communicating at all, probably because of the low signal-to-noise ratio). The latency measurements were stable, at 1ms.

2. Monterey Bay Coast Testing

After successfully making the baseline testing of the equipment, making sure everything was functional, the next step of the land-based testing began. The testing time was chosen as during the afternoon, when the fog or low clouds that could negatively impact the measurements are cleared by the sunshine. The first stop was to the first waypoint (Test Site 1) at a distance of 2.1Km from the fixed radios, and at an angle of approximately 48 degrees right of the sector antenna aim. This waypoint is in Best Western Beach Resort’s parking lot, near the Monterey Recreational Trail. It does not offer very good line-of-sight to NPS, as it is not near the beach and has some elevated sand dunes around it. Even after mounting the tripod at the highest point possible, connectivity was impossible, either with Wave Relay or with WiMAX. This indicates that even if at a close range, well within the 120-degree sector antennas coverage (both antennas gain pattern have approximately 95% of maximum gain for a 50-degree angle, according to the figures in the previous chapter), a very good line of sight without any physical obstacles in between is needed to get any connectivity.

The next stop was the next test site (Test Site 2) at a distance of 4.3Km, and at an angle of approximately 50 degrees. This point is across the Sand City shopping complex, between CA Highway 1 and the recreational trail, and offers better LOS to NPS. Then after connecting using TeamViewer to the server through 3G and powering up the Wave Relay master radio, a successful connection was made using the Wave Relay mobile radio, although the SNR was not very high (15.06 dB). By running the iperf script, an average bandwidth of 408Kbps was observed, but it fluctuated a lot (standard deviation 162). When pinging the server, an average latency of 7ms was observed, with a minimum measurement of 4ms and a maximum measurement of 11ms. The WiMAX radios, however, could not connect, although the wireless signal box in the radios' web interface was blinking green, indicating that they were picking up each other's radio waves, but these were not strong enough to establish a connection.

The next waypoint, Test Site 3, is by the Marina beach. The tripod was set up in the beach's parking lot, which is an elevated point (about 12 meters) and offered perfect visibility to the ocean. This was at 13Km away from the fixed radios at NPS, at an angle of approximately 35 degrees. The Wave Relay connection was successful, at a SNR of 15.84 dB, which is slightly better than that of the previous testing (although the distance had tripled). This is probably because of better LOS conditions and of a smaller incident angle. The average bandwidth measured by iperf was 936Kbps, with a standard deviation of 120. So the connection bandwidth was then much higher (more than doubled) and more stable, compared to the previous testing site. Pinging times were also improved, being constantly around 5 – 6ms. That said, a connection using WiMAX could not be made as the radio signal was still weak.

After the completion of the measurements, the next stop was Test Site 4, which was at the entrance to Moss Landing harbor (north shore). The distance was 25Km, and the angle is 28 degrees. Even though the testing point had direct LOS to Monterey and NPS, a connection could not be made using either Wave Relay or WiMAX. The WiMAX radios did not detect up any signal.

The decision was made to do two more tests to ensure being out of wireless range. The next testing site was an elevated point by Highway 1, north of Moss Landing (28.6Km distance, 28 degrees angle). That point, although not close to the coast, offers perfect LOS, since its elevation is about 35 meters, with low, flat land south of it. Unfortunately, there was failure again to connect using either WiMAX or Wave Relay, without detecting any wireless signal. The final test site overlooks Seacliff State beach in the Santa Cruz area. Distance is now 42Km, but the angle is only 5 degrees and the elevation is about 26 meters, with perfect visibility to Monterey Bay. No wireless signal, however, could be detected and no connectivity could be accomplished.

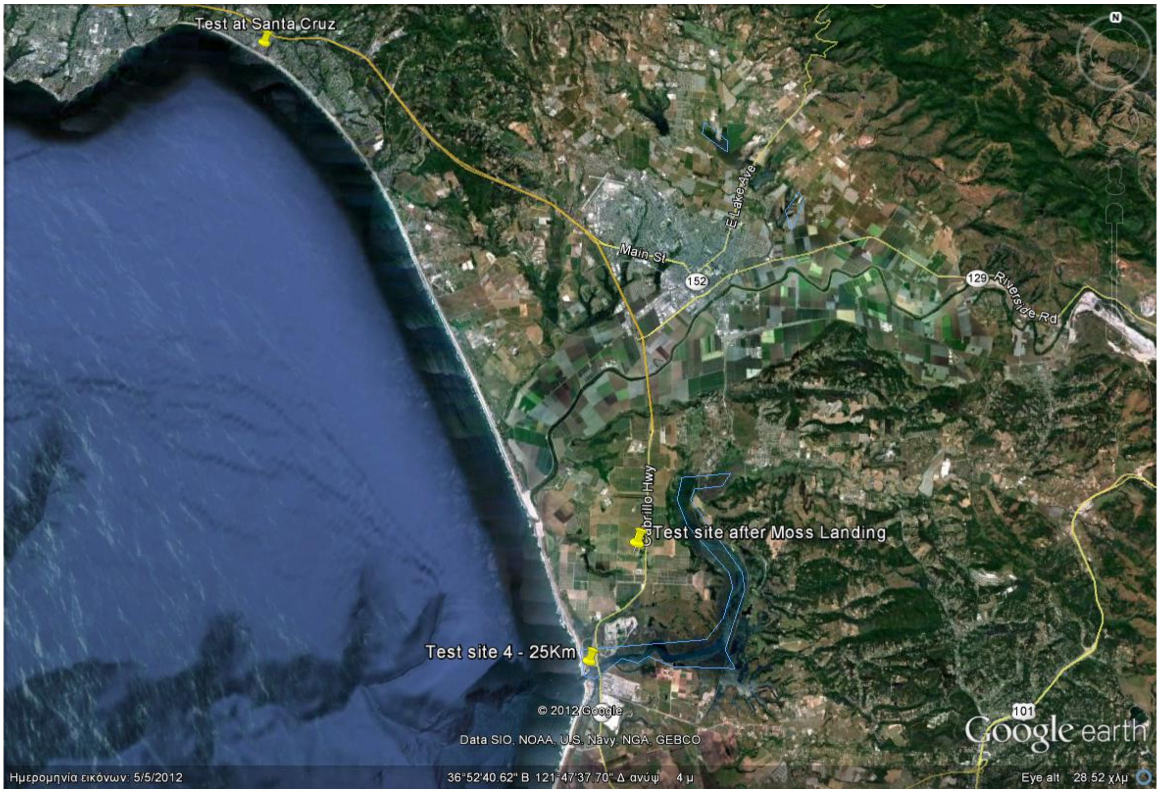


Figure 32. Additional land test sites

On the way back to Monterey, a further stop was made again at the Marina beach (Test Site 3) to make another Wave Relay test because low clouds and fog appeared. SNR was then 11.18 dB (compared to 15.84 dB previously in the day). Average bandwidth dropped to 571Kbps, and the average RTT increased to 16ms, with a standard deviation of 30.9ms and 4% packet loss. These results, compared with the previous ones for the same point, indicate that weather does indeed affect measurements.

3. Cellular 2G/3G Land Tests

A land test was also executed for the experiment's cellular connection, which serves as the "best case." The elevated point north of Moss Landing was chosen as the testing site. As described above, this was to achieve the best reception from the nearby cell towers. With 3 out of 5 bars for 3G connectivity, the average bandwidth observed from the Linux script is 941Kbps, which was also relatively stable. In addition, a bandwidth measurement was run from the Speedtest.net website (Ookla Net Metrics). The result is shown in Figure 34. Note that the comparable value to the experiment's script should be the upload speed, since iperf measures data sent from the mobile client to the server at NPS.

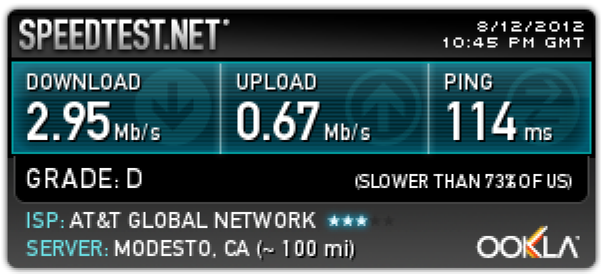


Figure 33. 2G/3G cellular connection speed test result on land

4. INMARSAT Satellite Tests

Satellite connectivity and performance is always the same, at least for a specific region covered by the same satellite. Thus, instead of carrying the INMARSAT BGAN device to the boat, the decision was made to perform testing on land. The test site selected was the same as above, north of Moss Landing: an elevated, rural area with no buildings or trees that might block the satellite signal. Any chance of interference is also minimized in this area. After setting up the BGAN and waiting for the satellite lock, the statistics captured are depicted in Figure 35.

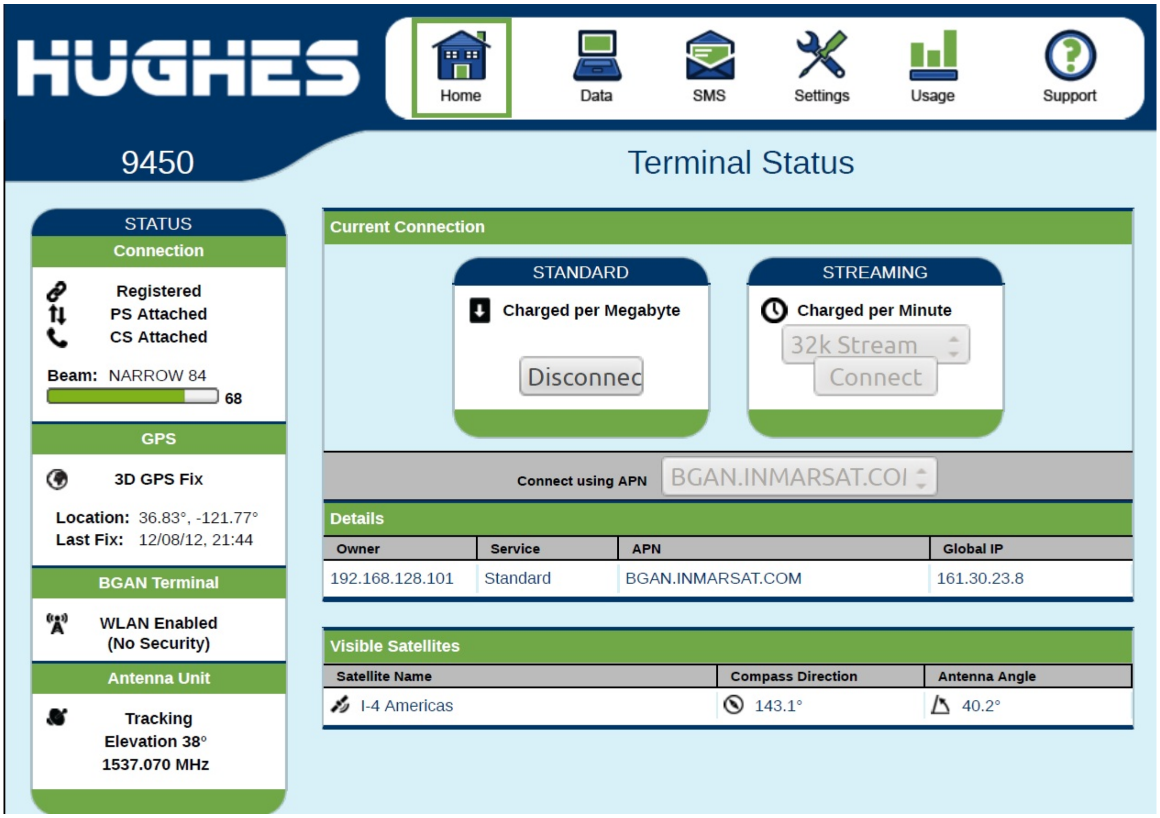


Figure 34. Hughes 9450 INMARSAT BGAN satellite connection statistics

The Linux script computed an average bandwidth value of 255Kbps. Similar to the 3G testing, a bandwidth test was run from Speedtest.net. The result is depicted in Figure 36. Note that RTT was then over 1 second due to the geostationary satellite's large propagation delays, as discussed in Chapter II.

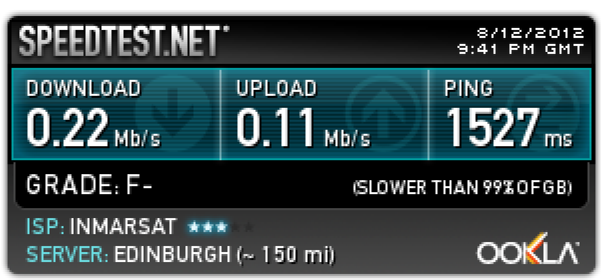


Figure 35. INMARSAT speed test result

B. SEA TRIAL RESULTS

With the land-based experiment results in hand; the next step was to test how WiMAX and Wave Relay would perform in the ocean surface environment. Since the furthest connectivity point in the preliminary testing was at Marina beach, and connectivity could not be achieved at Santa Cruz, the experimenters were certain that the Monterey Bay area would be sufficient for testing purposes.

The boat used was the Research Vessel (R/V) John H. Martin, owned by Moss Landing Marine Laboratories. The boat was docked at Moss Landing, so the plan was to move south along the coast, locating the furthest connectivity point with WiMAX and Wave Relay while in the right sector of the antennas' coverage area; then do tests close to NPS, near Fisherman's Wharf. The outbound course plan was in the antenna's left sector, i.e., to determine the furthest achievable connectivity point from NPS, as depicted in the previous chapter's figure, and then move west into the middle area of Monterey Bay to find the furthest connectivity point for 2G/3G cellular.

Figure 36. R/V John H. Martin [From 58]

The Wave Relay and WiMAX transmit power configuration was set to maximum. The Wave Relay configuration is depicted in Figure 38.

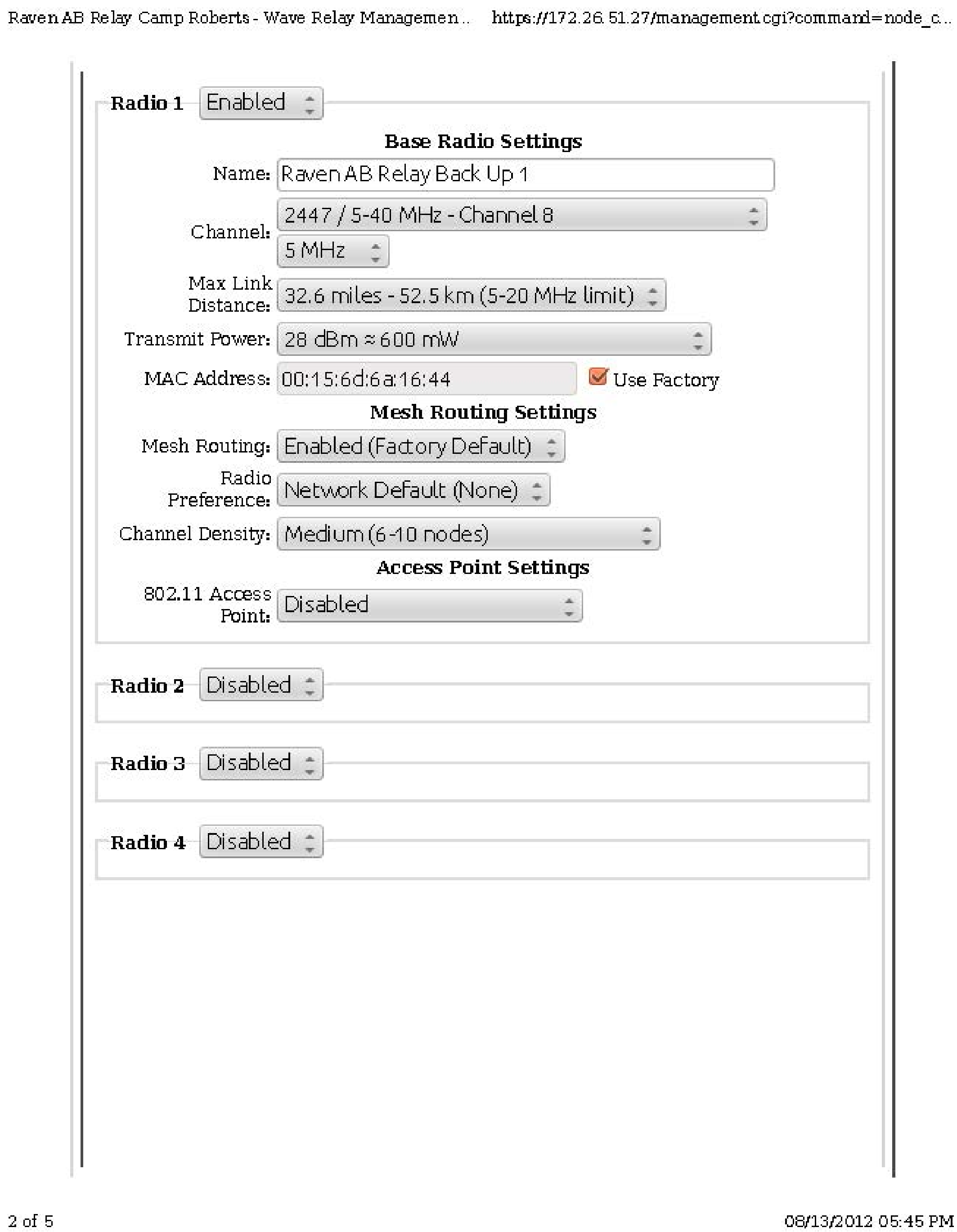


Figure 37. Wave Relay configuration during sea testing

While moving south from Moss landing towards Monterey, the first connection was acquired with Wave Relay at 13.6Km, at a 10-degree angle. Since the departure was in the afternoon, to save time, there was no stopping, but the iperf script was run. It was observed at an average bandwidth measurement of 1237Kbps. The bandwidth was not stable, however, mainly because of the constant movement and the rough sea state. WiMAX connection was not yet possible.

While arriving at the closest waypoint to NPS, at a range of 3Km, it was still not possible to connect with WiMAX, although the radio seemed to detect the signal from NPS. Wave Relay connectivity was present, but was very unreliable, as the SNR was very low, at 15.68 dB. After trying several points near the area, it was concluded that the trees along the NPS beach perimeter were mainly responsible for the signal problems. When moving westward, having a clear LOS to NPS and keeping the same distance, a stable connection was achieved with WiMAX. An even better connection was obtained while then moving to Point 0. This is depicted in the following figure. The Linux script measured an average bandwidth of 2122Kbps. Wave Relay connectivity was also greatly improved. SNR increased to 38.83 dB, and the average bandwidth was 707Kbps. While staying in the area, it was also noticed from the spectrum analyzer that lots of interference was received in the 2.4GHz range, which impacted the bandwidth for Wave Relay. These interfering signals were probably coming from land-based radio sources, like 802.11 wireless networks. In contrast, the 5.8GHz frequency range was interference-free.

Figure 38. Area affected by high trees between boat and NPS

With these lessons learned, a course was plotted northwest at 338 degrees, staying out of the ‘blind’ sector. As distance was increased from NPS, WiMAX connectivity was lost very quickly, right after the 3Km mark.

The next test point (Test Point 2, depicted in Figure 19) was 6Km from NPS and 15 degrees left of beam-center. The average bandwidth there for Wave Relay was 820Kbps and the SNR was around 38dB, without any interference in the 2.4GHz frequency area. There was still a faint WiMAX signal, so a bandwidth measurement for that system was also run. The script could not be completed, however, because the connection was intermittent and very unstable. The decision was made to manually run a quick iperf measurement before the signal was lost. An average bandwidth of 138Kbps was observed. The pings resulted in 69% packet loss with an average RTT of 12ms, but with standard deviation of 31ms.

The next move was to Test Point 3, 11.6Km away and at a 12 degrees left angle. Running only Wave Relay tests, an average bandwidth of 483Kbps was observed, at a SNR of 17.89 dB, which meant that the signal had weakened significantly.

At Test Point 4, a 15.6Km distance and maintaining the same angle, the SNR was 14.66 dB. Connectivity started to become unstable; average RTT from pings was 47ms, with a standard deviation of 137.6ms, and 9% packet loss. Average bandwidth was only 167.39Kbps, with a standard deviation of 93.3Kbps. Then continuing to move along the course northwest and at 17.7Km Wave Relay, connectivity was completely lost.

Having lost both of the experiment's private network connections, the course was set westward, away from the shore and the cell towers, to test 2G/3G cellular connectivity. At Test Point 5, 17Km from the northern point of Pacific Grove (the closest shore point), a 3G signal of 2 bars out of 5 was acquired in the AT&T MiFi. Average bandwidth was 686Kbps and average RTT was 137ms. After moving less than a mile westwards, however, the signal now was only 1 bar, while other AT&T phones in the boat did not connect. The last measurements were 174Kbps bandwidth and 197ms RTT just before the MiFi lost connection, too.

With all of the methods of data communication with the shore lost (except for satellite communications), the experimenters headed head back to Moss Landing, having completed the data collection, and were then ready to begin analyzing results and drawing conclusions from the experiment. While underway to Moss Landing harbor, the experimenters kept an eye on the radios (especially while passing the area in the center of the antennas' sector), in case any wireless signal was picked up from the base radios. Unfortunately, no further connections could be made. The next chapter presents results of the data analysis with recommendations for application, as well as areas requiring further study and experimentation.

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V. SUMMARY AND CONCLUSIONS

A. SUMMARY OF RESULTS

1. WiMAX Performance

The experimental results for WiMAX were much different than anticipated. As described in Chapter II, WiMAX has a theoretical range of up to 50Km, but in the experiment only an intermittent, unstable, and unreliable connectivity at 6Km was achieved. Part of the reasoning for this result is the use of a 120-degree sector antenna for the experiment's fixed radio (with a 16 dBi Gain) and of an omni-directional antenna for the mobile radio (with a 9 dBi gain). The free space loss for 6Km according to the formula:

$$L_{FS(dB)} = 20\log_{10}\left(\frac{4\pi df}{c}\right)$$

where d: distance (6×10^3 meters), f: frequency (5.8×10^9 Hz), c: speed of light, $\approx 3 \times 10^8$m/s, is calculated 123.27 dB. So the estimated receive power at 6Km, having a 25dBm transmit power, can be found as follows (assuming only free-space losses):

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{FS} = 25 + 16 + 9 - 123.27 = -73.27\text{dBm}.$$

In the experiment, it was found that the minimum receive power to successfully achieve a connection between the two radios was around -68dBm. So this analysis shows how this setup greatly decreases the total antenna gain, which in turn decreases the maximum range that can be achieved. This setup, however, is intentional as a sector antenna for the fixed station is needed to cover as much area as possible, since the ship in a real scenario won't be at a specific bearing at all times. Also the ship will be moving about, and it might change its heading at anytime. So for the experiment's mobile station, an omni-directional antenna has to be used. In other words, highly directional antennas would not be practical, although the use of a multi-input multi-output (MIMO) device might help.

Another potential issue is weather conditions: fog and low clouds that are present most of the time in Monterey Bay have a negative impact on the overall propagation conditions. The experimenters assume that the range would improve if a similar experiment took place elsewhere. Nevertheless, WiMAX's overall performance is much lower than anticipated.

In addition, the AN-80i radios are not very user-friendly, setup is not intuitive, and they need a long reboot time for each configuration change made.

2. Wave Relay Performance

Wave Relay proves to be a preferred option compared to WiMAX for the purpose of connecting a ship network with a shore network. It has a maximum coverage range of more than 17Km, where Wave Relay can still be used for low-bandwidth applications, like web-browsing, mail, or small file transfer, with the same antenna constraints. At a closer range of 11Km, bandwidth is around 0.5Mbps, which could be used to support real-time video applications. So the ship could stay at the edge of the coverage sector if it just needs to send some e-mails or photos, or move closer to the shore for more bandwidth-demanding implementations.

3. 2G/3G Cellular Performance

Cellular networks lead the way in terms of performance. Even at distant locations, more than 17Km away from the nearest shore, they still have 0.6Mbps throughput. RTT however, is much higher compared to Wave Relay, so they won't be as useful for real-time applications.

In the experiment, the cell tower's exact location is even further away, as it's usually placed on top of a hill to maximize its coverage area, and not near the coast. In addition, in the experiment only a simple USB MiFi was available inside the boat, instead of some more sophisticated 2G/3G antenna on the boat's mast, like Wave Relay or WiMAX. So 2G/3G cellular networks can be even more promising.

The other downside, except for the increased round-trip time propagation delay, is the use of a commercial network. This network cannot be controlled and manipulated like a Wave Relay or WiMAX private network, a feature that might be desirable for some ship-to-shore connectivity applications. Also, the ship's connectivity is more susceptible to denial of service (DoS), eavesdropping or other major security threats, as the encryption between the mobile device and the base station is weak for military standards.

4. INMARSAT Satellite Communications Performance

The experiment's satellite tests results were as expected. A throughput of 255Kbps was realized, which is close to the 432Kbps the company promises. RTT is very large, mostly over a second, but that was expected too, since the experiment's connection not only goes through the 500ms GEO satellite propagation delay, but also through INMARSAT company headquarters in the United Kingdom, as confirmed by the testing.

Thus a satellite communications link, which on top of being slow, is also much more expensive to use. It would only be the choice if there was no other option. In addition, it suffers from the same security threats as cellular networks, since it is mostly a commercial networking solution (at least for this experiment's purposes). This of course is not the case if a Navy ship uses government satellite systems, which are only accessible to certified users.

B. USE CASES

Given the above results, the experimenters derive some use cases for which one of these methods of ship-to-shore communications is preferable.

1. Navy Ship Operating in Coastal Waters

This use case assumes an operational theater similar to that of the Aegean Sea. The overall presence of a nearby coast would ensure that the warship is always within a 10 - 15 nautical mile radius from the nearest shore (e.g., small islands scattered in the area; see also Figures 1 and 2 in Chapter II depicting 2G and 3G coverage in the Aegean sea).

In this scenario, the most preferable solution would be a constellation of Wave Relay radios, installed in key locations on these islands (e.g., on top of navigation beacons). These radios should have 120-degree sector antennas, similar to that in the experiment, to balance range and coverage area. In some locations, sector antennas with a smaller sector angle and higher gain might be used to cover more distant areas. These Wave Relay radios would form a mesh network that would finally include a radio in the Navy's HQ.

In this way, the Navy ship would be connected to the HQ shore network, at speeds of around 500Kbps, depending on range. Real time applications that might be useful to the ship's mission (e.g., streaming video) are supported, since the RTT is very low. In addition, the ship itself could become part of the mesh that could enable other friendly ships nearby to connect, even if they are even further from the nearest coast. This private network is fully controlled and administered by the Navy, and is secured by the AES-CTR-256 encryption algorithm, as shown in Chapter III. Lastly, the overall infrastructure cost is relatively low, as the Navy would only have to purchase the Wave Relay radios and the antennas, placing them on existing structures.

2. Commercial Ship Operating in Coastal Waters

A commercial ship might prefer using a 2G/3G cellular network to connect to its company headquarters infrastructure. The cellular network requires no initial purchasing cost, and the range is better than Wave Relay. As long as the company is not interested in high security and real-time applications, this method of communications should be the most cost-effective solution. Should security become a significant issue, then it would be appropriate to pursue commercial-off-the-shelf encryption tools.

3. Commercial Ships Operating or Anchored Near Harbors

Here the range from the coast is short (well within the 6Km range WiMAX in the experiment), and a WiMAX solution might be considered. An 802.16 connection would offer very high bandwidth, which might be divided among users aboard the ship using either WiFi or Picocells. The examples of Washington State Ferries and Singapore's WisePort project analyzed in Chapter II illustrate these capabilities.

4. Navy and Commercial Ships Operating in Ocean Waters

These ships have no other choice but to use satellite communications for medium or higher rate data communications, since they are outside the range of any land-based network.

C. FUTURE WORK

1. Implementation of a Routing Algorithm

A ship (Navy or commercial) might have more than one option of connecting to the shore. In Use Case 1, above, for example, the Navy ship might also have access to a satellite network and a cellular network at the same time. So it could set up a router on board, properly configured and connected to the shore routers, which would seamlessly connect the ship to the shore network in a way similar to the IEEE 802.21 protocol. The connection method chosen would be set according to the parameters set in that routing algorithm. These parameters include overall bandwidth, round trip time, cost-effectiveness, security and simplicity.

2. Weather Impact in Ship-to-Shore Data Communications

The experiment took place in Monterey Bay, where a typical day has dense fog and low clouds. These weather conditions can have an impact on maximum range and bandwidth, especially for higher frequencies. This experiment's second bandwidth measurement at the Marina beach, as previously explained in Chapter IV, is also an indication that some weather conditions might have an impact on communications. Follow-up experiments in a variety of weather conditions might derive important results.

3. Methods of Improving WiMAX Range And Reliability

In this experiment, WiMAX connectivity had a short range and was not reliable. These results are much different than those expected. Perhaps a different hardware setup with different brands and up-to-date equipment will improve the WiMAX performance, extending its possibilities. Another alternative would be experimentation with various antenna types for the mobile node, particularly in various sea-states.

4. Interference Impact on Ship-to-Shore Communications

Wave Relay connectivity in very short range in this experiment was problematic. Interference from land-based wireless networks seemed to cause the problem, as shown by the spectrum analyzer. Other frequencies that are close or a fraction of this experiment's frequencies might also interfere. While the experiment's Wave Relay and WiMAX devices had the option of frequency change, in real deployed situation, changing the frequency for all of the radios might be a very expensive, costly, and time consuming operation. Research is needed into how other transmitting signals, especially those commonly found in coastal areas, might impact the ship's data communications. One such experiment might include the use of a quad-radio Wave Relay router, making use of 700 MHz, 900 MHz, 2,4 GHz, and 5.8 GHz bands.

In summary, this thesis explored the use of commercial-off-the-shelf radio technology as a means of providing ship-to-shore communications in littoral or brown water regions. In particular, it investigated the Wave Relay radios and Redline WiMAX radio, as well as Global Services for Mobile (GSM) cellular 3G data capability. Each technology offered potential for meeting this requirement.

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